sciendo Yearbook of the Poznań Linguistic Meeting 6 (2020), pp. 113–158
DOI: 10.14746/yplm.2020.6.5

Bilingualism and cognitive reserve: It's a matter of top-down or bottom-up process

Panagiotis Boutris
Florida International University, Miami
pboutris@fiu.edu

Jessica Rees
Swansea University

Brodie Bevan
Swansea University

Cristina Izura
Swansea University

Abstract

Cognitive performance declines with age following different trajectories. The cognitive trade-off, however, between age and cognitive reserve is still not clear. In addition, bilingualism has been thought to play a role in delaying cognitive decline by affecting cognitive control outside the scope of language. However, the effect has been unreliably reproduced and without exploring sufficiently the differences between cognitive functions that govern language control. In the current study 112 adults varying in age, level of bilingualism and cognitive reserve, completed a modified version of the Simon task, which engaged the mechanisms of interference suppression and shifting. Using ex-Gaussian analysis, the Simon effect was replicated in the normal component and the shifting effect was found in the exponential. Additional linear mixed-effects model analysis showed a significant "negative" effect of bilingualism on inhibition and a "positive" effect of cognitive reserve on shifting, both independent of age. Age affected similarly the speed of engagement of both executive functions irrespectively of language or cognitive background. Implications of a bilingual disadvantage and a beneficial effect of cognitive reserve during ageing are discussed.

1. Introduction

Cognitive performance declines with age. This decline has been characterised in terms of as decreased reaction speed (Salthouse 1996), reduced speed of visuospatial and verbal information processing (Fisk and Warr 1996; Lawrence et al. 1998), forgetfulness (Wang et al. 2011), distractibility and poor interference suppression (Hale et al. 1996), cognitive inflexibility and more effortful task switching (Perianez et al. 2007), decreased attentional control (Myerson et al. 1999) and working memory capacity (Gazzaley et al. 2005) among others.

However, the rate with which age-related cognitive decline progresses and symptoms occur varies significantly across individuals (Arbuckle et al. 1998). For example, Schmidt et al. (1999) found white matter lesions in ageing, but these lesions did not affect performance in all participants. Furthermore, Jack et al. (2000) have shown that, although older adults showed hippocampal atrophy, cognitive decline did not occur until three years later for some. The same pattern can be found in studies on neurodegenerative disorders, where the onset of the disease-related atrophy does not always match the onset of cognitive symptoms (Braak and Braak 1991; Amieva et al. 2008; Pérès et al. 2008). It is clear, therefore, that different brains deal differently with age-related neuronal pathology (Schaie and Zanjani 2006) and that factors outside the scope of normal ageing determine how early the symptoms of cognitive decline will occur. In addition, it is unclear how ageing affects different executive functions, particularly if these are being engaged with different frequency across individuals.

Stern (2002, 2009) proposed that differences in cognitive ageing are necessitated by differences in cognitive reserve (CR). In terms of neurofunctionality, CR refers to having more synapses to spare or alternative routes to use in an impaired brain (Barulli and Stern 2013; Fabiani 2012). Behaviourally, it has also been suggested that enhanced CR can actively enhance performance across age peers (Habeck et al. 2003; Stern 2012). Currently, there is not an accepted consensus on what constitutes as CR (Opdebeeck et al. 2016). However, factors that have been evidenced to enhance CR include socioeconomic status (Hackman and Farah 2009; Kaplan et al. 2001; Noble et al. 2005), educational level achieved (Le Carret et al. 2003; Schneeweis et al. 2014), socialising (Bowling et al. 2016; Inouye et al. 1993), physical and cognitive leisure activities (Mistridis et al. 2017; Scarmeas et al. 2001), work and professional responsibilities (Knight and Nigam 2017; Suo et al. 2012) and every-day procedural skills such as driving (Marioni et al. 2012; Valenzuela et al. 2009). Research on cognitive decline should, therefore, take into account these aspects of an individual's life experience. In the proposed study, questionnaires on the aforementioned CR aspects were collected and combined into a general score of CR for each participant.

Another aspect of cognitive lifestyle is the use or not of more than one language. In a bilingual[1] brain, both languages are actively competing (Costa and Sebastián-Gallés 2014; Green and Abutalebi 2013; Dijkstra et al. 1999; Pliatsi-

[1] Henceforth, an individual who uses more than one language will be referred to as "bilingual"; an individual who only knows one language will be referred to as "monolingual".

kas et al. 2015) and the bilingual speaker needs to suppress one of them in order to converse in the other. Two levels of suppression have been suggested: a top-down inhibition of the opposing language system (Green 1998; Kaushanskaya and Marian 2007; Kroll et al. 2014) and a bottom-up inhibition of each competing linguistic item within each language, for example words or syntactic clusters (van Heuven and Dijkstra 2010; Kroll et al. 2010). However, the effect of the prolonged suppression of the other language on cognitive performance and decline is still being debated.

The idea that bilinguals may outperform monolinguals in non-linguistic tasks[2] is known as "bilingual advantage" (Bialystok 2009). However, the evidence supporting such an advantage is equivocal. In a meta-analysis by Paap et al. (2015), the majority of studies investigating inhibitory control, monitoring, shifting, task engagement/disengagement and goal maintenance reported null effects of bilingualism compared to monolingual controls (Billig and Scholl 2011; Kirk et al. 2014; Paap and Greenberg 2013; Von Bastian et al. 2016). Even so, many studies that have reported a "bilingual advantage" (e.g. Engel de Abreu et al. 2012) have been impossible to replicate with the same results (Antón et al. 2014; Duñabeitia et al. 2014).

In contrast, a plethora of studies in favour of bilingualism suggest that bilinguals have enhanced cognitive functioning and slower cognitive decline (Bialystok et al. 2012; Luk et al. 2011a; see Bialystok 2018, for a review). Admittedly, the complexity of capturing the variations of the "bilingual advantage" can only be matched by the complexity of controlling for different levels of bilingualism[3] and the cognitive mechanisms at play during tasks used to explore bilingual differences (such as the Simon or Stroop tasks). Chen et al. (2014) found that even when controlling for many aspects of CR and different levels of bilingualism, the occurrence of the "bilingual advantage" was associated with specific types of cognitive control, namely inhibition and shifting.

Mediating the opposing sides, Duñabeitia and Carreiras (2015) criticised the term "advantage" and argued that bilingualism may be playing a more implicit role in shaping cognition than originally thought. Even though this seems more plausible, neuroimaging, however, has reported observable changes in the brain anatomy and functional connectivity during prolonged bilingualism (García-Pentón et al. 2014; Perani et al. 2003; Pliatsikas et al. 2015). This means that,

---

[2] This is observed traditionally as faster reaction times in inhibitory and/or switching tasks, selective attention and goal maintenance.

[3] Proficiency, age of acquisition, frequency of usage.

even if the effects of bilingualism may be too discrete to be captured behaviourally, the monolingual brain is indeed different from a bilingual brain (Hervais-Adelman et al. 2011). Research, therefore, on the "bilingual advantage" should focus instead on *why* these neuronal changes occur and link them to *different ways they may affect behaviour* rather than directly linking them to performance differences in behavioural tasks. In addition, researchers should consider that the effect might be (1) *mechanism-specific* rather than task-specific and (2) *moderating* (for example, through a possible enhancement of CR), rather than direct.

1.1. Mechanisms involved in bilingual control

If the bilingual effect is mechanism-specific, it is important to clarify which mechanisms will be investigated. Two executive functions will be tested in this study: inhibition (Diamond 2013) and shifting (Miyake and Friedman 2012). Both mechanisms are key to bilingual language control. For example, in a dual-code[4] bilingual conversation (Green and Abutalebi 2013; Bialystok et al. 2012) inhibition, or interference suppression, happens as the bilingual speaker inhibits competing linguistic items such as words or morphosyntactic regulations; it happens in the item level of the competing languages (Dijkstra et al. 1998) and it is considered a bottom-up, or "local", inhibition. As Bialystok et al. (2012) explain, even though the bilingual speaker is using one language at that moment (following one set of linguistic rules), each conflict is different and stimulus driven. In contrast, shifting resembles a "global" type of inhibition, necessary in order to suppress the active language schema in its entirety. It happens when the bilingual speaker needs to switch to the other language. This type of suppression is *goal-driven*. It is a collaboration of a *top-down* selection/suppression process whilst maintaining the relevant goal.[5] Miyake and Friedman (2012) described it as part of higher executive functioning, namely *shifting*.

In order to capture both executive functions in a non-linguistic context, an alternative version of the Simon task (Hedge and Marsh 1975; Simon and

[4] Green and Abutalebi (2013) define a dual-code, or "dual-language" interactional context as a conversation in which both languages are being used; language switching is, thus, frequent within the conversation, but each language is used only towards a different speaker. This can also be applied to cases where an internal monologue in one language is interrupted by an external interaction in the other language.

[5] In the case of the conversational context, the goal would be for the message that the bilingual speaker is conveying to "make sense" to the receiver.

Rudell 1967; Simon 1990) was devised. The goal of the task is to associate a specific colour of a stimulus with a specific response. The main principle of the traditional Simon task is that the speed of choice reaction depends on the spatial relationship between stimulus and response. This relationship is triggered automatically, even when the goal is to pay attention to the colour of the stimulus and not the location (Hommel 1993). In our version, the participants were required half-way through the task to change the initial associations between colour and stimulus, inducing the need of shifting whilst still ignoring the spatial interference (inhibition).

The Simon task was chosen due to its wide use in exploring cognitive control in ageing and bilingualism (Bialystok 2006; Davidson et al. 2006; Stürmer et al. 2002). It has also been the most unreliable task yet to measure the bilingual "advantage" (Paap et al. 2015), which could be attributed to the fact that bilingualism may not be "afflicting" the bottom-up and top-down processes in the same way (Chen et al. 2014).

1.2. Independence of bilingualism from CR

Prolonged bilingualism has been suggested to enhance CR (Bialystok et al. 2012) by means of delaying age-related decline of cognitive control (Grant et al. 2014; Gold et al. 2013) or delaying symptoms of neurodegenerative diseases (Craik et al. 2010; Schweizer et al. 2012). However, it is debatable if bilingualism should be given its own attention in an individual's cognitive lifestyle.

On one hand, it is logical to assume that bilingualism is an extension of CR. For second-language late-learners,[6] it is a type of learning; and learning is a key part of CR's underlying neuroplasticity (Li et al. 2014). On the other hand, in Bialystok's (2009) words, bilinguals do not have a "choice". They have to constantly exert a meta-linguistic cognitive control when language is involved (Green and Abutalebi 2013). For example, let us assume that practicing a sport, e.g. rugby, and learning its technique and dealing with the physical challenges may resemble the practicing and handling of two languages and the conversational challenges. What makes a bilingual different from a rugby player? The rugby player will not train all day every day, whereas a bilingual will even "take home" the training.

---

[6] Bilinguals who acquired their second language much later in life, especially after the critical period (6–7 years of age; Abutalebi et al. 2007).

In the current study, bilingualism is explored as a separate predictor of cognitive decline, outside CR. One reason for this is based on evidence linking bilingualism and occurrence of cognitive decline symptoms (Alladi et al. 2013; Bialystok et al. 2007; Craik et al. 2010; Schweizer et al. 2012). Bialystok et al. (2007) reported a significant delay of diagnosis of dementia between bilinguals and monolinguals, with bilinguals exhibiting a delayed diagnosis by roughly 4 years. Progression of the neuropathology was not monitored or compared, however, in the study. A better controlled study by Alladi et al. (2013) showed bilingual differences in the onset of symptoms of dementia based on the type of dementia (i.e. Alzheimer's Disease, Frontotemporal Dementia and Vascular Dementia). The type of dementia that showed the most delayed symptoms in bilinguals was Frontotemporal dementia (FTD). Their results can be interpreted as te bilingual brain handling better the damage to the areas that are most susceptible to FTD. The reason for this is because FTD affects predominantly brain areas involved with executive functions such as inhibition and shifting; functions that life-long bilinguals use more persistently (Bak et al. 2014; Soveri et al. 2011). Therefore, according to Alladi et al. (2013), those areas in bilinguals seem to be equipped to deal better with damage by being more developed i.e., for example, higher white matter integrity (Bialystok et al. 2012).

The second reason for separating bilingualism and CR is the complexity of measuring bilingualism. Bilingualism is a complex convolution of proficiency in both languages (Perani et al. 1998; Abutalebi et al. 2001), age of acquisition - AoA- (Brysbaert et al. 2000; Wartenburger et al. 2003; Abutalebi et al. 2007) and frequency of usage (Luk and Bialystok 2013; Green and Abutalebi 2013). An expert bilingual is a bilingual who is proficient in both languages, uses both of them regularly and has acquired them both at the early years of life. The more expert the bilingual, the stronger the competition between the languages; in consequence, the larger the engagement of inhibition and more often the engagement of shifting (Green and Abutalebi 2013). Questionnaires tapping into the aforementioned aspects of bilingualism were joined together for an overall score of bilingualism. The bilingual was considered part of a spectrum between two extremes: inexpert and expert bilinguals.

1.3. Independence of executive functions: the ex-Gaussian approach

Shifting and interference suppression will be examined through our version of the Simon task. It is not entirely clear whether shifting and interference suppression work independently or in conjunction with each other. Evidence on shared neuronal circuits between the two mechanisms exists (Dove et al. 2000; Marmolejo-Ramos et al. 2015; Swainson et al. 2003). However, they do not overlap entirely (Botvinick et al. 1999; Swick and Jovanovic 2002).

Step-wise, our Simon task involves the aforementioned mechanisms at different times. During the time-line between the stimulus appearance and the response, inhibition happens at the perceptual level. When the stimulus appears, the participant has to inhibit the task-irrelevant location association between the response and the stimulus. After inhibiting, the decisional part of the trial starts (Price et al. 2019). During this stage the participant has to make a choice based on a rule (in this case the task-relevant colour association between stimulus and response). These two mechanisms are mapped on different parts of the time-line of the trial (Wagenmakers 2009).

Consequently, different mechanisms are affected by different trial manipulations (Ratcliff et al. 2004). Mapelli et al. (2003) showed that the Simon effect is elicited by fast responses which tend to enhance automaticity. The automaticity of perception is what creates the task-irrelevant location association. When the authors increased the time between stimulus onset and response, the Simon effect decreased and then eventually reversed. This biphasic pattern of the Simon task suggests that looking for a Simon effect across the whole time-line of the reaction time may be meaningless (Zorzi and Umiltá 1995). In contrast, the mechanism of shifting is expected to be affected by the tail of the reaction time distribution. As a "more controlled" top-down process, the participant should engage shifting at the "decisional" part of the trial's time-line (Matzke and Wagenmakers 2009).

Traditional reaction time analyses (Gaussian means and standard deviations over the whole reaction time distribution) cannot capture the autonomy of the mechanisms mapped on the time-line of a trial (Ratcliff and McKoon 2008). One approach is the parametrisation of the distribution based on the ex-Gaussian model.[7] The ex-Gaussian model has been efficient in fitting reaction time data (Lacouture and Cousineau 2008). The advantage of looking at the two different distributional components lies in the detection of experimental manipulations that affect different processes (Buzy et al. 2009; Gu et al. 2013; Mapelli et al. 2003). These processes may be engaged at different time-points during the time-line of a trial.

---

[7] Based on the exponentially-modified Gaussian distribution, which is a convolution of a normal and an exponential distribution.

The interpretation of the ex-Gaussian model's two components is still debatable (Marmolejo-Ramos et al. 2015). Many researchers have advised against mapping executive functions on the two different distributions (Matzke and Wagenmakers 2009). The reason for this is that when the ex-Gaussian distribution was first noticed for its "good" fit on reaction time data, it arbitrarily received many interpretations of its components. Since then, a plethora of different cognitive mechanisms have been attributed to each component, the least common denominator being that the normal variant is comprised of lower cognitive processes that are more automated (such as motor planning of an action, response inhibition and cue detection and perception of the stimulus), whereas the exponential variant is affected by higher top-down mechanisms that tap into the strategies that lead to a choice reaction (Hockley 1984). In addition, arguments against the autonomy of each process in the brain has made the theoretical interpretations of ex-Gaussian models even more spurious (Marmolejo-Ramos et al. 2015).

However, we argue that the allocation of the processes to the two different distributions of the trial's time-line should not be based on the "nature"[8] of the processes, but on the *stage* they are elicited. If a mechanism is elicited at the perceptual level, it is significantly automated (Kornblum and Lee 1995; Umiltà and Nicoletti 1985); if it is elicited at the decision-making stage, it is more controlled (Voss et al. 2015). There have been cases, for example, Calabria et al. (2011), where perceptually elicited processes, such as "inhibition" in the Flanker task, were mapped on the exponential component of the ex-Gaussian model. The authors re-analysed two studies, applying the ex-Gaussian approach. However, as the authors state, their choice of task was driven solely by what had already elicited strong results in their favour.[9] Specifically, the version of the task included 75% of the trials as congruent and 25% as incongruent, introducing possible confounding effects of expectation, a process that forms its own top down rules during a task (Summerfield and Egner 2009).

In our current study, we revisit the idea that the Simon effect should be explored in the normal component, as a mechanism that is being elicited at the perceptual level. In contrast, shifting should be explored at the exponential component, as part of the decision-making stage. The validity of the assumption

---

[8] How autonomous they may be from each other or if they are supposedly higher executive functions.

[9] The authors only considered the version of the task that showed a bilingual effect on the speed of processing and the magnitude of the conflict effect.

of using the ex-Gaussian model to fit our reaction time data is also revisited by fitting various possible models, as advised by (Marmolejo-Ramos et al. 2015). In addition, if we were to look for the effect of inhibition and shifting in their opposite components (respectively exponential and normal), we would expect a biphasic pattern for both effects. This would be in accordance with the biphasic pattern of the Simon effect that Mapelli et al. (2003) reported.

1.4. The current study

Mapping the ex-Gaussian distribution on the adapted version of the Simon task, it was explored how life-long bilingualism may predict cognitive control and cognitive decline across the lifespan in high (shifting) and low (interference suppression) executive functioning. CR was also explored as a confounding factor on how cognitive performance may be enhanced and maintained during ageing. Measuring bilingualism and CR as a spectrum allowed us to recruit participants varying in age, as opposed to recruiting "same age" groups. This was considered a better way to look at the cognitive trajectory across the life-span.

Grouping the subjects based on age cut-offs was avoided. This approach was considered significantly insensitive to data-points near the borders of those arbitrary groups. Therefore, we implemented linear mixed-effects modeling (LME). In addition, the reason the linear regression model was avoided as a possible candidate was due to the lack of intra-subject variability. One of the advantages of the LME procedure is the ability to account for individual variability, based on the full dataset and not calculated averages. This is depicted by the inclusion of random effects and slopes in an LME model (Bates et al. 2012). Therefore, the parameters of the fixed effects[10] are calculated by taking into account these random effects (ε). The ε refers to general within-subject baseline differences in reaction times (1|*subject*). Furthermore, the ability to include random slopes in model parametrisation accounts for additional idiosyncratic differences in how each subject will react/perform under the different experimental conditions (1 + *congruency*|*subject* or 1 + *shifting*|*subject*). Consequently, as compared to linear regression models, the parametrisation of LME models can result in more accurate subsequent power estimations (Johnson et al. 2015) and in better replication power (Brysbaert and Stevens 2018; López-López et al. 2014).

The following research questions were put forward:

[10] I.e. the independent variables in which a researcher is interested.

- *How do the two executive functions decline during ageing?* We hypothesise that more years of age will predict longer reaction times for both distributions (normal and exponential). In addition, interference suppression and shifting will also be affected. The prefrontal cortex has been found to be most susceptible to age-related changes. This is known as the frontal lobe hypothesis (West 1996). The prefrontal cortex is a core hub for cognitive control (Cabeza et al. 2000; Prakash et al. 2009). Therefore, ageing should affect both interference suppression and shifting in a similar way by increasing each of their effect.
- *Can CR predict better cognitive performance in older age?* CR has been shown to affect cognitive prowess and how the brain deals with age-related neuropathology (Opdebeeck et al. 2016; Stern et al. 2019). We expect an interaction between age and CR. Participants with higher levels of CR should show a moderate increase in RTs across age. In contrast, participants with lower levels of CR should show a significantly steeper increase in RTs across age.
- *Does prolonged bilingualism predict better cognitive control in older age?* Independently from CR, bilingualism should affect the size of the effect of inhibition and shifting. Based on the bilingual "advantage" theory, language control engages generic cognitive control mechanisms. Therefore, as more expert bilinguals have more experience in language control, they will show better conflict resolution, i.e. smaller sizes of Simon and shifting effect. In addition, an interaction between age and bilingual expertise is expected. More expert bilinguals should observe a moderate increase of the effects of shifting and interference suppression during ageing.

2. Method

2.1. Participants

One hundred and twelve healthy participants living in Wales took part in the study. Participants had different language and educational backgrounds. All of them were adults, aged 18 and over (range 18-85 years old, 77 females). Prior to participation, each individual was given a consent form to sign and reported normal or corrected-to-normal vision. All subjects completed our version of the Simon task and a battery of questionnaires during a 45 minute session. In Figure 1, histograms of the subjects' age, bilingual expertise and level of CR are presented. The variables were centred around zero (z-scores) for bilingualism and CR.

2.2. Apparatus and stimuli

2.2.1. Simon task

A computerised version of the Simon task was programmed using the open source platform PsychoPy (Peirce 2007) and presented using a DELL computer with a screen resolution of 1920x1080. The stimuli used for the Simon task comprised of two circles of red and blue colour, created with GIMP 2.0 and presented on a dark grey background (see Appendix F). The circles were presented during the experiment on either side of the screen following a centered white fixation cross. The responses were recorded using the laptop's QWERTY keyboard; the keys "A" and "L" were chosen as the two spatially opposite responses.

Participants were instructed to use the index fingers on their left and right hands to press, respectively, either the key "A" or "L", ignoring the spatial dimension of the stimulus (i.e. on which side of the screen the circles would appear) and focusing their answer only on the colour of the circle. They were instructed to answer as quickly and accurately as possible. Each trial would start with a white fixation cross to draw the participants attention to the centre of the screen. After a fixed 500 ms period, the stimulus would appear in either side of the screen awaiting a response for 2000 ms. The moment a response would be made, the current trial would end and the participant would move on to the next one. In case the 2000 ms were exceeded, the trial would automatically end and the absence of a response would be recorded as incorrect.

In the first block, a specific association between the colour and the response key was given to the participant, replicating the established Simon task (Simon and Rudell 1967). After the first block was presented, a very short break took place (no more than 3 minutes) during which the participants were given different instructions; they were instructed to reverse the association between colour and response key, resulting in suppression of the previous instructions (shifting) as well as being faced with the congruency effect (inhibition). The order of the associations between the colours and the response keys was counterbalanced.

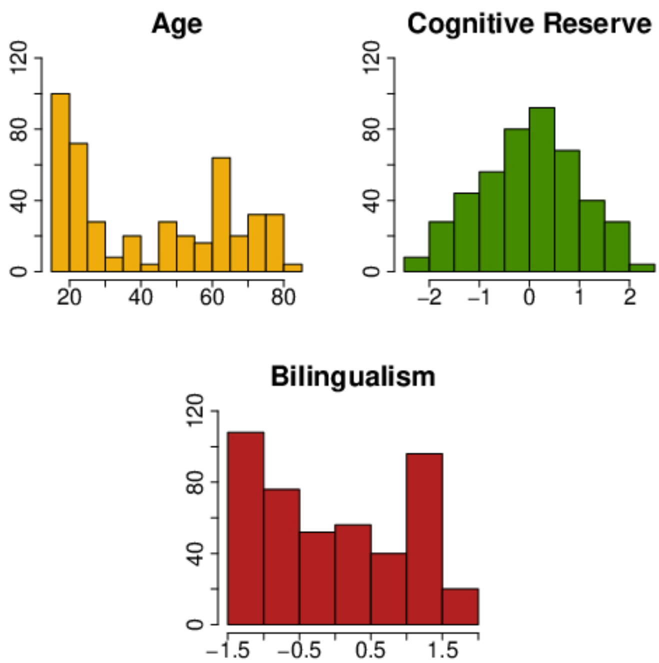

Figure 1. Histograms of each independent variable are presented.

The experiment consisted of a practice and two experimental blocks. In the practice block, 14 congruent and 14 incongruent trials were given. Each experimental block consisted of 80 congruent and 80 incongruent, resulting in a total of 320 experimental trials. In the first block, an initial association between stimulus and key would be created. After a short break (no more than 3 minutes), the second block would begin with the instruction to reverse the initial association between key and colour.

After the task, the questionnaires were administered.

2.2.2. Questionnaires

For collection of demographic information and the assessment of the participants' cognitive and bilingual status, three questionnaires were designed and administered (see Appendix A).

Demographic and Language Background questionnaire: The questionnaire concerned general demographic information, including gender, age, nationality and where participants lived or live. In addition, questions included subject's occupation, level of education, socioeconomic status, social and cognitive life-style, physical activities, marital situation and simple every-day skills such as driving and handling smart electronic devices. As an extension to people's socioeconomic status, there were questions about parents' or caregivers' educational level and occupation. Further, the participant's native language was recorded as well as their knowledge of a second language. Factors such as age of acquisition of second language, language at home, language contact and self-scores of proficiency were collected.

Bilingual Questionnaire: In addition to the main questionnaire, a bilingual questionnaire was created for a more accurate self-assessment of the proficiency of the second language and the *frequency* with which participants used any of their second languages. In addition, specific second-language skills such as writing, reading, speaking and listening were examined in more detail.

3. Data pretreatment

Reaction times on the Simon task were recorded and following a distributional analysis (ex-Gaussian), two different time-lines were allocated to two different executive functions: inhibition and switching/shifting. In addition, measures of participants' level of bilingualism and the level of CR were extracted.

3.1. Questionnaire data

For the scoring scheme of the questionnaires, three main measures were taken into account: *age*, *bilingualism* and *cognitive reserve*. Bilingualism and cognitive reserve scores were standardised on a continuous scale. Higher level of bilingualism describes a more balanced and "experienced" bilingual and presumably a stronger competition between languages. A higher level in cognitive reserve describes a higher brain reserve capacity and presumably more preserved cognitive control.

For a detailed description of how these measures were computed see Appendix B. In Table 1, correlations are explored between the predictors for possible highly co-varying independent variables. Age and CR show a significant negative relationship, albeit medium. The correlation was probably partially driven by factors such as education and socioeconomic status, which were part of CR; today's older generation has lower education levels attained due to less resources available in the past and less qualifications needed. In addition, older adults should exhibit a lesser degree of involvement in CR related activities. No significant correlation was found between between bilingualism and CR. Our measures, thus, seem to tap into different cognitive aspects with CR relating more to academic attainment and generic cognitive skills, whilst bilingualism relating more to language control and acquisition.

Table 1. Correlation coefficients for each pair of fixed effects (predictors).

Pearson's			
	BI	CR	Age
BI	1.00		
CR	0.16	1.00	
Age	0.07	−0.52***	1.00
p < 0.01**, p < 0.001***			

3.2. Response time data

All RTs below 150 ms were removed (fast outliers) and all RTs above 1600 ms (slow outliers). Eighteen participants were excluded from the analysis for exhibiting more than 20% of incorrect responses, misses, fast and long outlying responses. From the remaining 112 participants and a total of 38,680 trials, a 15.3% of trials were excluded as inaccurate responses.

Based on AIC,[11] ex-Gaussian was selected as the "best fit" for our data. See Appendix C for a detailed description of model comparison.

The reaction time (RT) distribution was fitted via the Ex-Gaussian model with a Gaussian parameter μ and an exponential parameter τ. For each participant in each condition, the parameters μ and τ were inserted in a repeated measures 2×2 ANOVA with the two within-subjects conditions comprised of

[11] Akaike Information Criterion.

the Simon effect (*congruent vs. incongruent*) and the block effect (*shifting vs. no shifting*). Table 2 shows the averaged ex-Gaussian parameters of the normal distribution, the mean (μ) and standard deviation (σ), and of the exponential distribution (τ) across conditions.

Table 2: Mean (mu) and standard deviation (sigma) of the normal variant and mean of the exponential variant (tau) across all conditions.

	Shifting			No shifting		
	$\bar{\mu}$	σ	$\bar{\tau}$	$\bar{\mu}$	σ	$\bar{\tau}$
congruent	0.406	0.046	0.117	0.397	0.043	0.163
incongruent	0.447	0.049	0.106	0.434	0.045	0.151

4. Results

4.1. Ex-Gaussian analysis: Simon and shifting effect

Due to the nature of the two effects and their link to the two distinct time-lines of the ex-Gaussian distribution, we looked for the Simon effect in the normal variant (μ) and for the effect of shifting in the exponential variant (τ) of the ex-Gaussian model. A main effect of congruency (Simon effect) was found with $F\mu(1, 111) = 46.81$, $p < 0.001$; the average response time was longer for the incongruent trials ($\mu incongruent = 0.440$ s) than for the congruent ($\mu congruent = 0.402$ s) across both blocks. In addition, the effect of shifting (block effect) was significant with $F\tau(1, 111) = 60.25$, $p < 0.001$. The direction favoured the trials where there was no switching involved, with longer average RT for the shifting trials ($\tau shifting = 0.157$ s) than for the no shifting trials ($\tau noshifting = 0.112$ s). In Figure 2 the effects of the two mechanisms on RT can be seen.

In addition to the above analysis, both effects were also explored in their respective opposite distributions. The Simon effect was tested in the exponential component, which showed a significant reversed pattern. The shifting also exhibited a biphasic pattern when tested in the normal component. This replicates the biphasic pattern that Mapelli et al. (2003) described. In the case of the Simon effect, when explored at the tail of the distribution (exponential variant), its effect decreased until it completely reversed. Similarly, the shifting effect, when looked at the early components (the normal variant), its effect decreased till it completely reversed. For the purposes of the study, the biphasic patterns were not considered informative and were excluded from further analyses.

Based on the cumulative density function (CDF) for the normal variant (top plot), the average density in the distribution of the congruent condition (blue line) is located at smaller RTs (shift to the left). In contrast, the density of the distribution of incongruent trials (red line) culminates at slower rates (shift to the right). This replicates the Simon effect, where the congruent trials are responded faster to than incongruent trials.

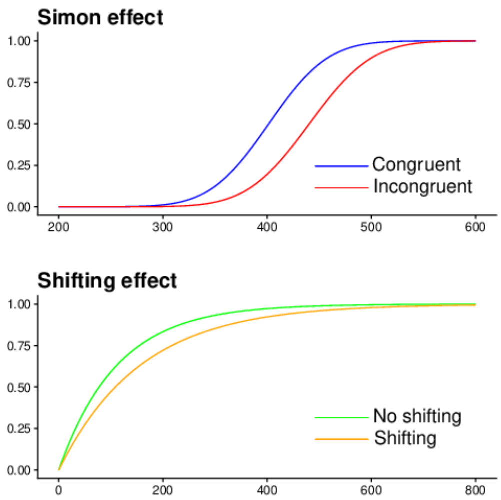

Figure 2. Cumulative density distributions of the Simon and block (shifting) effect across the two variants of the ex-Gaussian model, the normal (μ) for the Simon effect and the exponential (τ) for the shifting effect.

Based on the cumulative density function (CDF) for the normal variant (top plot), the average density in the distribution of the congruent condition (blue line) is located at smaller RTs (shift to the left). In contrast, the density of the distribution of incongruent trials (red line) culminates at slower rates (shift to the right). This replicates the Simon effect, where the congruent trials are responded faster to than incongruent trials.

The CDF for the exponential variant (bottom plot) depicts the shifting effect. Trials at the first block (green line) were responded faster (shift to the left) than trials at the second block (yellow line), where participants had to change instructions (shift to the right). This implies that the engagement of shifting affects performance but at the tail (exponential variant) of the distribution.

4.2. Age, bilingualism and CR on executive functioning

For the main *linear mixed model* analysis, three (3) models were constructed: **(a)** the *Simon effect model (SiM)* for which the Gaussian parameter μ was the dependent variable; **(b)** the *shifting effect model (ShM)*, for which the exponential parameter τ was treated as the dependent variable; and **(c)** the *executive control model (ExC)* where the size of the Simon and shifting effect were the dependent variables. The size of the each effect was calculated by subtracting the relative parameter (μ or τ) of the "easy" condition (i.e. congruent or no-shifting) from the "difficult" condition (i.e. incongruent or shifting respectively). For the formula of the initial models see Appendix D.

We implemented the stepwise backward rejection procedure (*lmerTest*[12]), with Kenward-Roger's approximation for the degrees of freedom[13], in order to look for the minimum number of necessary predictors for each model. During each model selection, the alpha was set as

$$\frac{alpha(0.05)}{no.of possible models}$$

to avoid overparametrisation. The final models were:

- $SiM_{full} = \mu \sim congruency + age + BL + congruency : BL + (1 + congruency|subject)$
- $ShM_{full} = \tau \sim shifting + age + CR + shifting : CR + (1|subject)$
- $ExC_{full} = effect \sim control + BL + CR + control : BL + control : CR + (1|subject)$,

[12] R package for "Tests in linear mixed effects models" developed by Kuznetsova et al. (2015, 2017).

[13] The Kenward-Roger method of approximation was chosen as a more conservative alternative to the Satterthwaite's approximation, since the former has been shown to not be affected as much by the complexity of the covariance structures, the sample size or imbalance of observations (Kenward and Roger 1997; Schaalje et al. 2002).

where *control* is the type of CC (inhibition or switching) and ":" indicates an interaction; BL refers to the measure of bilingualism and CR to the measure of cognitive reserve. Note that bilingualism was deemed an optimum predictor in the SiM model but not in ShM. In contrast, CR was deemed an optimum predictor in the ShM model but not in the ShM. In addition, only in the case of the SiM model the random slope for the congruency factor (1 + *congruency*|*subject*) was deemed optimum.

All three full models were fitted[14] and compared with their direct "reduced" versions, in order to assess the "significance" of the each predictor. All reduced models would differ by 1 df where possible (Winter 2013). For example, in the case of SiM, in order to check for the interaction of bilingualism and congruency, the following two models were compared:

- $SiM_{full} = \mu \sim congruency + age + BL + congruency : BL + (1 + congruency|subject)$
- $SiM_{interaction} = \mu \sim congruency + age + BL + (1 + congruency|subject)$.

In all model comparisons, polynomial trends were evaluated by using orthogonal polynomial contrast coding.

4.2.1. The Simon effect Model (SiM)

Using the likelihood ratio test (Bolker et al. 2009; Pinheiro and Bates 2006), in the model SiM[15], we found a significant interaction between congruency and bilingualism ($\chi^2(1) = 8.445$, $p < 0.01$). The main effect of age was significant ($\chi^2(1) = 65.494$, $p < 0.001$), but no interaction was found with either bilingualism or congruency. The model was also assessed for its random slope (1 + congruency|subject), which was found to be significant ($\chi^2(2) = 9.4337$, $p < 0.01$). In Table 3, the average estimates and the standard errors for each fixed effect of the model SiM are shown; in addition, the variance for the random slope for each level of congruency, their correlation and the residual are also presented. In the case of the congruent condition, the estimate given is the difference from the intercept, i.e. the incongruent condition. In order to calculate the average estimate for the congruent condition, a simple addition would suffice: estcongruent = 284.66 + (−19.44).

---

[14] The models were fitted using the statistical language R (R Core Team 2013) and the mixed effects analytical tool lme4 (Bates et al. 2012).

[15] $SiM = \mu \sim congruency + age + BL + congruency : BL + (1 + congruency|subject)$

Table 3. Summary of the SiM model. The estimates are shown in milliseconds.

Fixed Effects	Estimate	Std. Error	Random Effects	Variance	Std. Dev.	Corr
incongruent	284.66	16.53				
congruent	−19.44	2.75	incongruent	5866.95	76.60	
age	3.16	0.34	congruent	125.19	11.19	0.75
BL : incongruent	0.12	7.72	Residual	2884.7	53.71	
BL : congruent	−8.10	2.76				

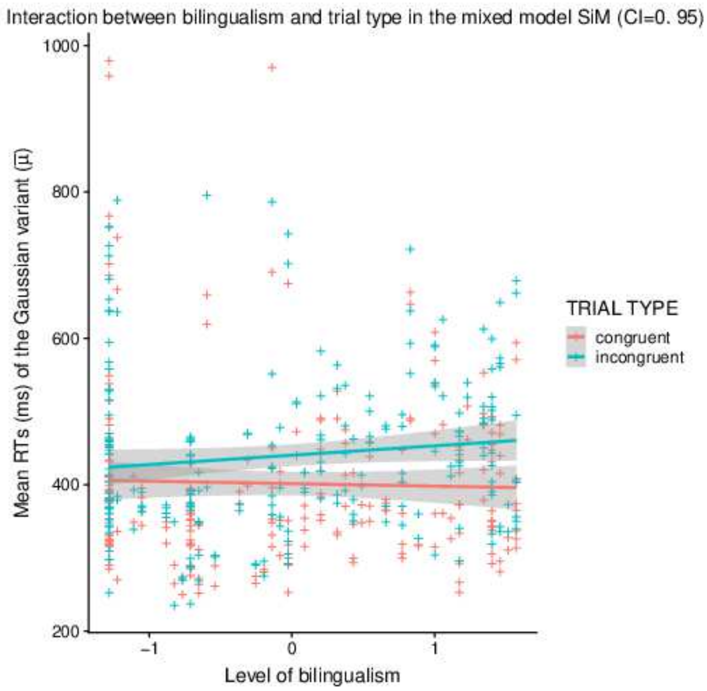

Figure 3. The slopes (lines) and raw data (points) for each level of trial type (colours) across the level of bilingualism (BL); the grey bands show the confidence intervals, which are set to 0.95.

In Figure 3, the interaction is depicted by how higher levels of bilingualism may have a "detrimental" effect on the response to the difficult trials, i.e. the incongruent trials (blue line/dots). In contrast, the congruent trials (red line/dots), where there is no conflict between stimulus and response location, seem to not be significantly affected. In Figure 4, the main effect of age can be seen more by the steepness of the line: the older the participant the slower the response (larger RTs), independently of condition or level of bilingualism.

However, when we simulated[16] the results based on the model's coefficients (see Table 3), the power estimation for the interaction showed a weak replication rate (26.7%), whereas congruency and age reached 97.3% and 100% (results of the simulation can be found in Appendix E as part of the assessment of each model).

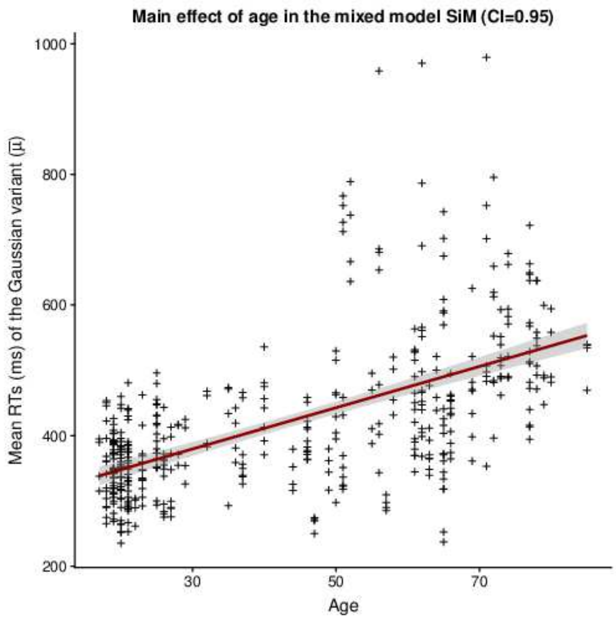

Figure 4. The slope (line) and raw data (points) of the Gaussian RTs (μ) across age; the grey band shows the confidence intervals, which are set to 0.95.

[16] The simulation was done based on 1000 samples following the procedure that was described by Brysbaert and Stevens (2018). For a full description of the procedure and linearity assumption check, see appendix E.

4.2.2. The Shifting effect Model (ShM)

In the ShM[17] model, the comparisons showed a significant interaction between CR and shifting ($\chi^2(1) = 5.514$, $p < 0.05$) and a main effect of age ($\chi^2(1) = 13.019$, $p < 0.001$). Table 4 summarises the model's estimates for both fixed and random. In the no shifting condition, the estimate given is the *difference* from the intercept, i.e. the shifting condition. The average estimate for the no shifting condition (block 1) can be calculated by addition: $estnoshifting = 94.01 + (-22.50)$. The "(Intercept)" variable under the random effects section indicates the within-subject variance.

Table 4. Summary of the ShM model. The estimates are shown in milliseconds.

Fixed Effects	Estimate	Std. Error	Random Effects	Variance	Std. Dev.
shifting	94.01	11.93			
no shifting	−22.50	2.60	(Intercept)	1758	41.93
age	0.93	0.25	Residual	3026	55.01
CR : shifting	−0.64	5.56			
CR : no shifting	6.14	2.61			

In Figure 5 the interaction can be seen clearly on how higher levels of CR may have a "beneficial" effect on the difficult block, i.e. the block where shifting is exerted (blue line/dots). In contrast, the no shifting block (red line/dots), where there is no need for switching to new instructions, is not affected significantly. In Figure 6 the main effect of age is depicted with older participants responding slower (larger RTs), independently of condition or level of cognitive reserve.

Simulation confirmed the effects, with interaction between shifting and CR reaching 100% power and the main effect of age 99.1% (see Appendix E).

[17] $ShM = \tau \sim shifting + age + CR + shifting : CR + (1|subject)$

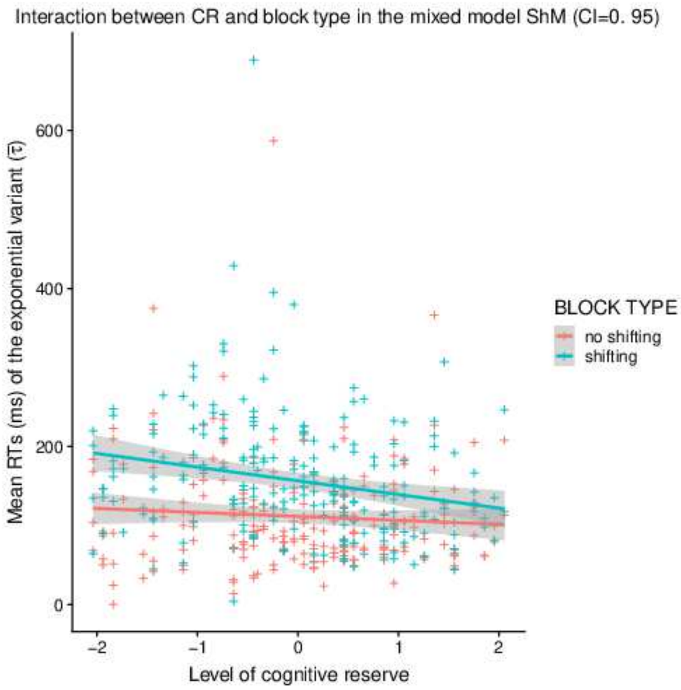

Figure 5. The slopes (lines) and raw data (points) for each level of the block type (colours) across the level of cognitive reserve (CR); the grey bands show the confidence intervals, which are set to 0.95.

4.2.3. The Executive Control Model (ExC)

The results for the ExC[18] model showed that both interactions were significant with $\chi^2(1) = 7.094$, $p < 0.01$ for the interaction between bilingualism and type of control, and $\chi^2(1) = 4.650$, $p < 0.05$ for the interaction between CR and type of control. The estimates and standard errors, as well as the variance and standard deviations, for the fixed and random effects respectively are shown in Table 5.

[18] ExC = effect ~ control + BL + CR + control : BL + control : CR + (1|subject)

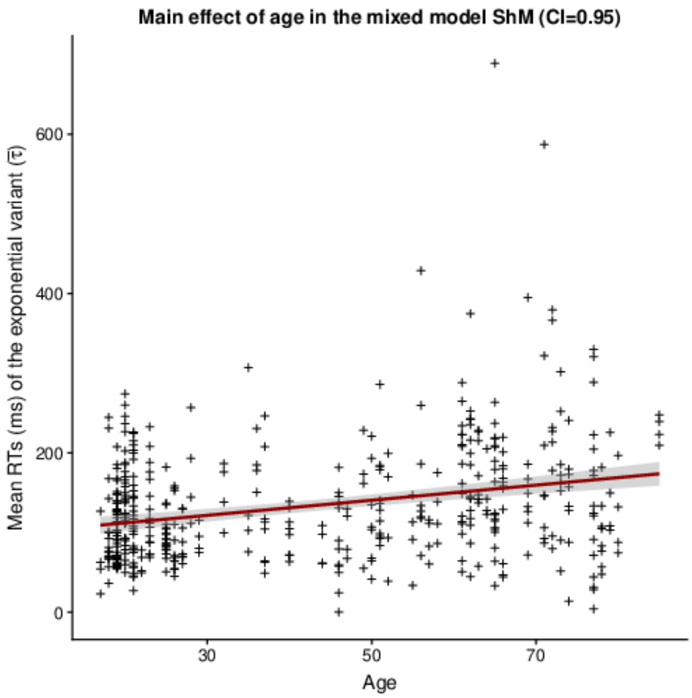

Figure 6. The slope (line) and raw data (points) of the exponential RTs (τ) across age; the grey band shows the confidence intervals, which are set to 0.95.

For inhibition, the estimate given is the *difference* from the intercept which represents switching. The average estimate for the inhibition level of control can be calculated as: $est_{inhibition} = 41.94 + (-3.06)$. The "(Intercept)" variable under the random effects section refers to within-subject variance. Regarding the interactions, the coefficients that are given match the type of control (condition) where the effect was most prominent: *bilingualism* * *inhibitory* and *cognitivereserve* * *shifting*, showing the "negative" effect that bilingualism has on inhibition (longer RTs as bilingualism increases) and the "positive" effect that CR has on shifting (faster RTs as CR increases).

Table 5: Summary of the ExC model. The estimates are shown in milliseconds.

Fixed Effects	Estimate	Std. Error	Random Effects	Variance	Std. Dev.
switching	41.94	4.74			
inhibition	−3.06	3.03	(Intercept)	1488	38.57
BL	7.79	4.83	Residual	2060	45.38
CR	−5.56	4.83			
BL : control	8.24	3.09			
CR : control	−13.27	6.18			

The interactions are depicted in more detail in Figure 7. Each type of cognitive measure (bilingualism or CR) affects different types of control. More specifically, higher levels of bilingualism predict **larger** effect sizes only for inhibition, whereas switching remains "unaffected". On the other hand, higher levels of CR predict **smaller** effect sizes, but only for switching. Power estimation based on 1000 simulations revealed 100% probability of replication for both interactions (see Appendix E).

5. Discussion

The aim of the current study was to investigate how cognitive reserve and bilingualism can explain the age-related variability of cognitive decline. Cognitive performance was measured by general speed of responding (RTs) and by how efficiently the mechanisms of inhibition (Diamond 2013) and shifting (Miyake and Friedman 2012) were engaged in an enhanced version of the Simon task (Simon 1990).

In this version, the Simon task resembles what would happen in a bilingual conversation. As proposed by Green and Abutalebi (2013) and Bialystok et al. (2012), when a bilingual has to switch between languages, they exhibit a *global* type of control, during which they inhibit the whole language system and change to the new required language system. This is a top-down mechanism called shifting and it is goal driven; the goal being to speak in a different language. Bilinguals also exhibit a more local type of control, inhibition, at the lexicomorphosyntactic level (Guo et al. 2011), by inhibiting the competing structures of the other language. By using the Simon task, the bilingual "advantage" on age-related cognitive decline was explored in a non-language domain. It was hypothesised that more expert bilinguals would be less affected by the Simon effect and by the shifting effect (faster RTs and smaller effect sizes) and by age (less steep decrease in speed).

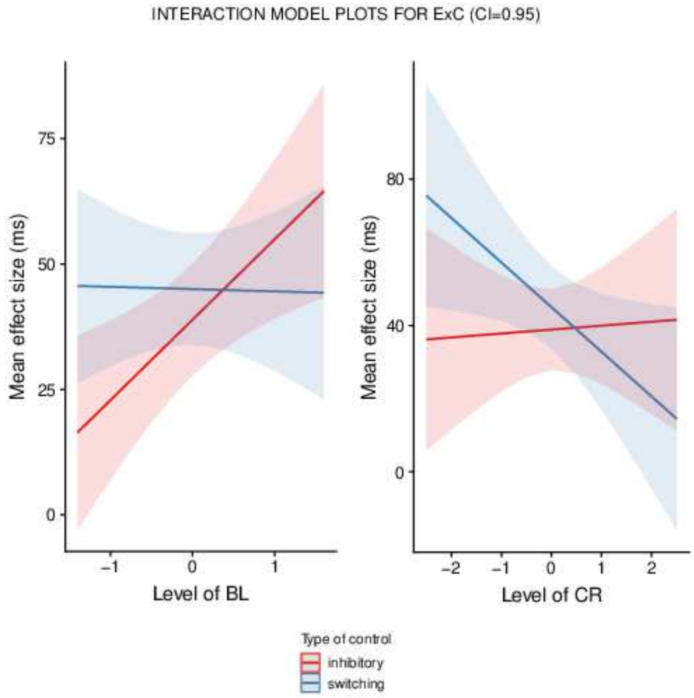

Figure 7. The predicted slopes (lines) for each type of control (colours) across the level of bilingualism (BL) and cognitive reserve (CR); the bands show the confidence intervals, which are set to 0.95.

Cognitive reserve (CR) was considered as another factor that could explain cognitive decline in ageing (Opdebeeck et al. 2016; Stern et al. 2019). CR derives from a combination of life experiences, routines and activities and as such it is considered a very fluid construct (Nucci et al. 2012; Rodríguez et al. 2011). However, it is an important aspect of cognition as it affects age-related cognitive decline, either by slowing down the neuropathology of age or delaying its symptoms (Cabeza and Dennis 2013; Nyberg et al. 2012; Zahodne et al. 2015). It was hypothesised that higher levels of CR would predict faster RTs in the Simon task and lower rates of age-related cognitive decline (less steep decrease in speed).

Three mixed models were fitted; the SiM model, in which conflict resolution at the item level (inhibition), age and bilingualism seemed to affect reaction time; the ShM model, where shifting, age and CR significantly predicted reaction time; lastly, the ExC model was fitted in order to further explore the relationship between the two cognitive mechanisms and the measures of bilingualism and CR. For convenience, we will refer to the reaction times of the normal component of the ex-Gaussian model as "*early-RTs*" and for the exponential as "*late-RTs*".

5.1. Inhibition and shifting

The Simon effect showed the expected direction in the normal variant of the distribution (μ); the incongruent trials showed significantly slower response times than the congruent trials. This is a direct replication of the Simon effect (Simon 1990); the task-irrelevant spatial relationship that is automatically created between stimulus and response is resolved by inhibiting the irrelevant spatial information. Our results confirm this. In addition, the Simon effect was found in the normal variant of the ex-Gaussian model, the early-RTs. This suggests that interference suppression is indeed a bottom-up process highly *automated* (De Jong et al. 1994). Examples where participants had to delay their responses, the effect was not present (Bari and Robbins 2013). This implies that inhibitory control is linked to a network that it is perception-related and not strategy-related.

A significant shifting effect was observed when participants switched between instructions in the exponential variant (late-RTs). More specifically, shifting resulted in longer late-RTs in the second block (reversed instructions) as compared to the first block. However, the overall slowed down performance was found only at the "strategic" level of the switching trials, when the decision-making takes part. The longer late-RTs indicate the need to suppress in the second block the association between colour and response button that had been created in the first block. This is a case of task-switching, during which the selective response inhibition (suppressing the pre-potent response from the previous set of rules) and the task disengagement/engagement take place. This sequence of executive functions constitutes mental shifting (Green and Abutalebi 2013; Miyake et al. 2000).

The location of inhibition and shifting in the ex-Gaussian distribution implies that the mechanisms are elicited by different processes (perceptual and strategic respectively). The model, therefore, of Green and Abutalebi (2013) is supported by our findings. According to their model, during a switching incongruent trial, the participant is presented with the stimulus. At first, the participant has to inhibit the response-stimulus location. Then, a decision needs to be made based on a set of instructions. This is when they engage shifting, i.e. they inhibit the pre-potent rule that was created during the first task (the first set of rules or the first language), they disengage from the previous task/rules and engage in the new set of rules. This time-line has been observed in similar paradigms (such as the Stroop task). In such tasks, lower inhibitory control is associated with the normal variant. In contrast, higher task switching mechanisms are associated with the exponential variant of the ex-Gaussian model (Steinhauser and Hübner 2009).

As neuronal reactions are instantaneous and work in parallel, we cannot argue for a clear sequential occurrence of events/mechanisms. Expressly, Marmolejo-Ramos et al. (2015) have criticised separating the two mechanisms of interference suppression and shifting due to sharing a "central mechanism". However, we argue that both mechanisms are elicited by different processes. We consider interference suppression as a stimulus-driven (bottom-up). In contrast, shifting seems to be driven by a higher process than interference suppression, because it is driven by a conscious suppression of the set task inertia, i.e. the first "mental" rules (Bialystok et al. 2012; Meuter and Allport 1999; Swainson et al. 2003). Furthermore, neuroimaging studies have indeed supported a different, albeit partly overlapping, network for each process. On one hand, bottom-up inhibition has shown a right hemisphere lateralisation with main circuits involving right anterior cingulate cortex (ACC), right involvement of prefrontal cortex (PFC), basal ganglia and only the pre-supplementary motor area (pre-SMA); on the other hand, top-down shifting has been shown to involve activation in a much more bilateral network: left ACC, left dorsolateral PFC, left SMA and the left intra-parietal sulcus (Dove et al. 2000; Botvinick et al. 1999; Garavan et al. 1999; Swainson et al. 2003; Swick and Jovanovic 2002). Extending further than inhibition and shifting, this differential topography has been shown to generalise to other bottom-up and top-down mechanisms respectively (Dove et al. 2000; Mink and Thach 1993; Monchi et al. 2001).

5.2. Age and executive functioning

Both SiM and ShM models showed a main effect of age. More years of age significantly predicted slower early-RTs and late-RTs. This suggests that age-related cognitive decline affects processes at all levels, sensorimotor (early-RTs) and strategic (late-RTs).

Age and the normal component: the SiM model. The normal component in the ex-Gaussian model is characterised by a normal distribution of response times (early-RTs). This is typical when performances from a large variety of human perceptual and motor processes are averaged (Madden et al. 2004). Accordingly, the effect of age on the early-RTs captures the decline of the highly automated processes such as attention/perception, motor-planning and motor-execution (Lacouture and Cousineau 2008). This has already been observed in paradigms such as the Stroop task (Larson et al. 2009; Kerns et al. 2004), the Eriksen flanker task (Botvinick et al. 1999; Clayson and Larson 2011) and the Simon task (Duthoo et al. 2014).

During early-RTs, interference suppression is engaged. However, it is not evident if age affected early-RTs only through the decline of attentional/perceptual and motor processes. It is possible that the speed with which interference suppression was called into action was affected as well. By applying a similar dual mechanism model (Braver et al. 2007), Larson et al. (2016) observed smaller slower engagement of reactive[19] mechanisms, described by slower latencies and smaller amplitudes of the ERN component[20] during ageing. It is, therefore, possible that age increased early-RTs also by decreasing how fast interference suppression was engaged for the Simon conflict resolution.

Age and the exponential component: the ShM model. Age also slowed down the late-RTs. The exponential distribution (late-RTs) is believed to be the result of decision processes (Luce et al. 1986) or top-down proactive allocation of attention resources (Braver et al. 2007). In this regard, decision-induced processes also declined during ageing. If we assume that the automated processes were fully captured by the early-RTs, then the increase in late-RTs in older participants may be indicating that executive functions such as shifting are also engaged with a delay during ageing.

---

[19] In the dual mechanism model of cognitive control proposed by Braver et al. (2007), reactive cognitive refers to bottom-up detection of interference or errors.

[20] Induced by a perceptual process as the interference suppression in our Simon task.

Age and sustained conflict: the ExC model. The exclusion of age from the ExC model, as indicated by stepwise rejection method, implies that the size of the Simon effect or the shifting effect was not affected during ageing. As we have seen in models SiM and ShM, age could predict the speed of engagement of the two mechanism, but not the "*quality*" of the engagement per se. Studies have indeed shown a sustained magnitude of conflict adaptation through-out ageing (Larson et al. 2016; Puccioni and Vallesi 2012; West and Moore 2005). A possible explanation is that older adults tend to focus more on accuracy at the expense of speed (Lucci et al. 2013; Will et al. 2008). This complicates interpretations regarding the effect of ageing on the condition of the networks involved in interference suppression and shifting. This is where RT studies fall sort. Valuable information comes from neuroimaging studies where the significantly extended activation of the dorsolateral prefrontal cortex during conflict tasks indicates a necessary larger recruitment of additional cognitive resources (Botvinick et al. 2001); this neuronal activity suggests that the older brain needs more resources to sustain the magnitude of conflict at the same level as a younger brain. However it seems it succeeds behaviourally.

5.3. A bilingual *disadvantage* for interference suppression

An interaction between bilingualism and congruency was found at the early-RTs (SiM model). However, the direction of the effect was opposite from what was initially expected. Higher levels of bilingualism predicted worse performance (longer early-RTs) in the incongruent trials, where the conflict was taking place. This implies that a non-linguistic conflict is getting harder to "manage" when you have to "manage" already a linguistic conflict: bilingualism. It is possible that bilingualism, instead of "leverage", may be acting as a burden on cognitive control.

Bilingualism has been already associated with burdened interference in linguistic domains. Poor performance of bilingual individuals in language tasks such as picture-naming, lexical decision, lexical recall, verbal fluency, word recognition through noise, and many others, has been widely documented (Gollan et al. 2002, 2005, 2007; Kaushanskaya and Marian 2007; Portocarrero et al. 2007; Ransdell and Fischler 1987; Roberts et al. 2002; Rogers et al. 2006; Rosselli et al. 2000). Even in everyday life, bilinguals experience cases of "tip of the tongue" utterances (Gollan and Acenas 2004) due to interference from the other language that could not be successfully suppressed. However, this burdened control has been predominantly observed in aspects of cognition involving language. Our results propose that the "bilingual disadvantage" may be at play even in a non-linguistic environment.

What is the source of the disadvantage? Both languages in a bilingual individual are active and constantly competing (Bialystok 2018; Dijkstra et al. 1999; Green and Abutalebi 2013). As such, it is possible that bilingualism often intensifies any additional demand for interference suppression. This also explains why higher bilingual expertise seems to be linked in with larger interference; more equal competitors make for harder competition and harder subsequent resolution (Green and Abutalebi 2013).

Notably, the effect of bilingualism was restricted only at the mechanism of interference suppression. Bilingualism was rejected by the ShM model. In addition, the ExC model showed that higher bilingual expertise predicts specifically larger inhibitory effects but was unrelated to shifting effects. A possible explanation is that during the Simon task, the visualisation of colour unconsciously activated the lexical term for that colour. Studies have shown that language is activated when perceiving colour (Regier and Kay 2009; Siok et al. 2009; Thierry et al. 2009) and, in cases, it dictates its perception. It is possible that during colour perception, the activation of the lexical representation of the colour term in both languages[21] may have started a competition at the lexical item. This competition between colour terms engages a type of local inhibition (Bialystok et al. 2012; van Heuven and Dijkstra 2010) similar to interference suppression (Green 1998). Similarly, if switching to the other language had happened long before the task, the language shifting effect would not have been engaged during the task, which could explain the absence of the "bilingual disadvantage" from the shifting effect (ShM model).

The power estimation based on simulation did not reach conventional (<80%) significance in the SiM. This casts doubt on how reliably the SiM model captured the "bilingual disadvantage" on inhibition. As a measurement, bilingual experience does not have a standardised battery. Frequency of usage, proficiency and age of acquisition are good candidates, but there is not a consensus on how these factors interact. Nevertheless, the successful replication of the significant interaction between inhibitory effect size and bilingualism in the ExC model (>80%), suggests that language control weighs on reactive control processes. However, the lack of an interaction between shifting and bilingualism may also be suggestive of how challenging it is to define a non-language do-

[21] The dual activation has been noted in bilingual Stroop tasks (Colomé 2001).

main, where neither aspects of language control (namely interference suppression and shifting) are already engaged.

5.4. Cognitive reserve

An interaction between block condition (no shifting and shifting) and CR in the ShM model significantly predicted the speed of late-RTs. Higher CR scores predicted faster late-RTs in the second block (where shifting was taking place), indicating that CR may be helping with maintaining performance during demanding circumstances; in this case, during the engagement of shifting.

Notably, CR affected late-RTs when task switching was present whereads CR did not predict any differences in the no shifting condition. During no conflict, CR seems to have no "special" benefit. This suggests that the benefit that CR may offer can be observed only in challenging mental circumstances. In accordance with Stern's (2002) concept of brain reserve, CR can offer cognitive purveyance (Barulli and Stern 2013; Fabiani 2012; Stern et al. 2019). It is a matter, therefore, of number of resources available (and their cross-functionality), which the brain can use in order to perform demanding tasks efficiently (Bush and Shin 2006; Gould et al. 2003; Sunaert et al. 2000). Efficiency, thus, as seen in this experiment, is synonymous with maintaining the speed of responding[22].

The ExC model revealed that CR significantly predicted the shifting effect size; higher CR scores predicted smaller shifting effect sizes. It is possible that the pattern we saw above (higher CR scores for faster late-RTs) is an epiphenomenon of the fact that CR reduced the magnitude of conflict of switching. In addition, CR could not predict the size of the Simon effect, suggesting that networks benefiting from the aspects of CR we measured (viz. education, socio-economic status and leisure activities) are executive functions engaged by proactive processes. This has already been observed in studies where higher CR scores were associated with problem-solving, reasoning, complex attention and working memory functions (Roldán-Tapia et al. 2012). These aspects of cognitive control are what Salthouse and Davis summarised as fluid intelligence or cognitive flexibility (Salthouse and Davis 2006; Salthouse et al. 2008) and represent predominantly higher executive functions (Miyake and Friedman 2012;

[22] This is usually in cases of choice-reaction tasks, where the subjects are always instructed to answer as quickly as possible.

Monchi et al. 2001), which are dependent on wider networks than lower "specialised" executive functions (Diamond 2013; Dove et al. 2000; Mink and Thach 1993).

5.5. The Simon task as a measure of executive functioning in bilingualism

Our results showed a clear Simon effect in the early-RTs (the normal variant of the ex-Gaussian distribution). It seems that the task captures the low-level, bottom-up inhibitory process, which is in accordance with literature that has used the Simon task as a measure of inhibitory control (Diamond 2013; Davidson et al. 2006). However, only the SiM model showed a disadvantageous interference from bilingualism. This suggested that bilingualism may indirectly interfere with inhibitory performance by increasing language conflict. In contrast, the top-down process of shifting remained unaffected (bilingualism was removed from the ShM model).

As already mentioned, the use of the Simon task to explore the "bilingual advantage" has resulted in divergent outcomes (Paap et al. 2015) with some studies observing bilingual advantages Bialystok (2006) whilst others not Hilchey et al. (2015). Therefore, bilingualism may not be affecting the same way the bottom-up and top-down processes (Chen et al. 2014). In their reported findings, Chen et al. (2014) observed that higher self-regulation processes, such as cognitive flexibility, were directly more sensitive to differences in bilingual status than low-level processes. This suggests that the low-level regulation of inhibition in tasks such as the Simon task may not be able to capture the mechanisms that are directly affected by bilingualism. The fact that the bilingual effect did not reach conventional power (<80%) in the SiM could be due to this limitation. In addition, the separation of distributions based on the ex-Gaussian model may have indeed helped the sensitivity of the Simon task to bilingualism. However, it is still unclear how direct this effect is on the actual inhibitory process which is at play here.

Accordingly, the irregularity with which the "bilingual advantage" has been observed in other studies during the Simon task might be due to an irregular *carryover* effect from a higher executive function (that could or could not be sensitive to bilingualism) onto the executive function of inhibition (Simon effect). This case was depicted by Hilchey et al. (2015) in their review of Schroeder and Marian (2012) results; the initially thought "bilingual advantage" was driven by monolinguals responding faster on conflict-free trials and not by bilinguals responding faster on the conflict trials. Therefore, the Simon task was either capturing a low-level disadvantageous effect on conflict-free trials in bilinguals or was instead capturing differences unrelated to bilingual status. Future research on bilingualism should focus on the *nature* (top-down or bottom-up) of the control that could eventually be affected by the bilingual status. Subsequently, it is important to choose the respective tools/paradigms that can induce and measure the respective process.

6. Conclusions

The current paper investigated the varying effect of bilingualism and cognitive reserve on age-related cognitive decline. Two executive functions were explored using the Simon task: interference suppression and shifting.

Although these processes are not strictly sequential, they allocate in parallel different attentional resources that can be either highly reactive (such as interference suppression) or proactive (shifting). This two-dimensional time-line of the Simon task was clearly captured by our ex-Gaussian distributional analysis.

Results showed that age affects the speed of highly automated processes such as attention, motor-planning and motor-execution. The age effect was observed as a slow-down of reaction time at the normal variant of the ex-Gaussian model. In addition, age affected speed of engagement of executive functioning. More specifically, age seemed to delay how fast interference suppression (at the normal variant of the ex-Gaussian model) and shifting (at the exponential variant of the ex-Gaussian model) were engaged. This suggests that the speed of executive functioning in both reactive and proactive stages of a choice-reaction task worsens by age.

In contrast to the speed of engagement, magnitude of conflict was sustained during ageing. Effect sizes of both the Simon and the shifting effect were not affected by age. Age, thus, affected only the speed of engagement and not the "quality" of engagement of cognitive control. Behavioural data, however, is not able to offer a sufficient explanation to whether this is an epiphenomenon of a possible trade-off. It is possible that the null effect sizes were due to the ageing brain using more resources whilst maintaining the efficiency of executive functioning. Future studies should account for how "much" the brain works to maintain the quality of control.

Regarding the individual's language and cognitive background, bilingualism increased the congruency effect, by acting as a *disadvantage* against interference suppression. Presumably this is due to the fact that the more expert the bilingual, the more substantial the competition between the two languages at the item level. Consequently, this serves to worsen inhibition of other types of interference, in our case interference suppression. In contrast, cognitive reserve decreased the shifting cost, but not interference suppression. If shifting is a network that relies on other sub-networks, it can then rely on complementary resources if some sub-networks are already compromised due to ageing. CR seems to dictate, thus, how extended these complementary resources are or how efficiently the brain uses them.

Overall, our findings support that bilingualism and CR are different aspects of an individual's cognitive behaviour, with the former working as a disadvantage and the latter as an advantage in ageing. In order to tap into the effects of one or the other, both have to be properly accounted for.

References

Abutalebi, J., Brambati, S.M., Annoni, J.-M., Moro, A., Cappa, S.F. & Perani, D. 2007. The neural cost of the auditory perception of language switches: an event-related functional magnetic resonance imaging study in bilinguals. *Journal of Neuroscience* 27(50). 13762–13769.

Abutalebi, J., Cappa, S.F. & Perani, D. 2001. The bilingual brain as revealed by functional neuroimaging. *Bilingualism: Language and Cognition* 4(2). 179–190.

Abutalebi, J., Della Rosa, P.A., Ding, G., Weekes, B., Costa, A. & Green, D.W. 2013. Language proficiency modulates the engagement of cognitive control areas in multilinguals. *Cortex* 49(3). 905–911.

Akaike, H. 1998. Information theory and an extension of the maximum likelihood principle. In *Selected papers of Hirotugu Akaike*, pp. 199–213. Springer.

Alladi, S., Bak, T.H., Duggirala, V., Surampudi, B., Shailaja, M., Shukla, A.K., Chaudhuri, J.R. & Kaul, S. 2013. Bilingualism delays age at onset of dementia, independent of education and immigration status. *Neurology* 81(22). 1938–1944.

Amieva, H., Le Goff, M., Millet, X., Orgogozo, J.M., Pérès, K., Barberger-Gateau, P., Jacqmin-Gadda, H. & Dartigues, J.F. 2008. Prodromal Alzheimer's disease: successive emergence of the clinical symptoms. *Annals of Neurology* 64(5). 492–498.

Antón, E., Duñabeitia, J.A., Estévez, A., Hernández, J.A., Castillo, A., Fuentes, L.J., Davidson, D.J. & Carreiras, M. 2014. Is there a bilingual advantage in the ant task? evidence from children. *Frontiers in Psychology* 5. 398.

Arbuckle, T.Y., Maag, U., Pushkar, D. & Chaikelson, J.S. 1998. Individual differences in trajectory of intellectual development over 45 years of adulthood. *Psychology and aging* 13(4). 663.

Bak, T.H., Nissan, J.J., Allerhand, M.M. & Deary, I.J. 2014. Does bilingualism influence cognitive aging? *Annals of neurology* 75(6). 959–963.
Bari, A. & Robbins, T.W. 2013. Inhibition and impulsivity: behavioral and neural basis of response control. *Progress in neurobiology* 108. 44–79.
Barulli, D. & Stern, Y. 2013. Efficiency, capacity, compensation, maintenance, plasticity: emerging concepts in cognitive reserve. *Trends in cognitive sciences* 17(10). 502–509.
Bates, D., Maechler, M., Bolker, B., et al. 2012. lme4: Linear mixed-effects models using s4 classes. r package version 0.999999-0.
Bialystok, E. 2006. Effect of bilingualism and computer video game experience on the simon task. *Canadian Journal of Experimental Psychology/Revue canadienne de psychologie expérimentale* 60(1). 68.
Bialystok, E. 2009. Bilingualism: The good, the bad, and the indifferent. *Bilingualism: Language and cognition* 12(1). 3–11.
Bialystok, E. 2018. Bilingualism and executive function. *Bilingual cognition and language: The state of the science across its subfields* 54. 283.
Bialystok, E., Craik, F.I. & Freedman, M. 2007. Bilingualism as a protection against the onset of symptoms of dementia. *Neuropsychologia* 45(2). 459–464.
Bialystok, E., Craik, F.I. & Luk, G. 2012. Bilingualism: consequences for mind and brain. *Trends in cognitive sciences* 16(4). 240–250.
Billig, J.D. & Scholl, A.P. 2011. The impact of bilingualism and aging on inhibitory control and working memory. *Organon* 26(51).
Bolker, B.M., Brooks, M.E., Clark, C.J., Geange, S.W., Poulsen, J.R., Stevens, M.H. H. & White, J.-S.S. 2009. Generalized linear mixed models: a practical guide for ecology and evolution. *Trends in Ecology & Evolution* 24(3). 127–135.
Botvinick, M., Nystrom, L.E., Fissell, K., Carter, C.S. & Cohen, J.D. 1999. Conflict monitoring versus selection-for-action in anterior cingulate cortex. *Nature* 402(6758). 179.
Botvinick, M.M., Braver, T.S., Barch, D.M., Carter, C.S. & Cohen, J.D. 2001. Conflict monitoring and cognitive control. *Psychological Review* 108(3). 624.
Bowling, A., Pikhartova, J. & Dodgeon, B. 2016. Is mid-life social participation associated with cognitive function at age 50? results from the british national child development study (ncds). *BMC Psychology* 4(1). 58.
Bozdogan, H. 1987. Model selection and akaike's information criterion (aic): The general theory and its analytical extensions. *Psychometrika* 52(3). 345–370.
Braak, H. & Braak, E. 1991. Neuropathological stageing of alzheimer-related changes. *Acta Neuropathologica* 82(4). 239–259.
Braver, T.S., Gray, J.R. & Burgess, G.C. 2007. Explaining the many varieties of working memory variation: Dual mechanisms of cognitive control. *Variation in Working Memory* 75. 106.
Brysbaert, M. & Stevens, M. 2018. Power analysis and effect size in mixed effects models: A tutorial. *Journal of Cognition* 1(1).
Brysbaert, M., Van Wijnendaele, I. & De Deyne, S. 2000. Age-of-acquisition effects in semantic processing tasks. *Acta Psychologica* 104(2). 215–226.

Bush, G. & Shin, L.M. 2006. The multi-source interference task: an fmri task that reliably activates the cingulo-frontal-parietal cognitive/attention network. *Nature Protocols* 1(1). 308.

Button, K.S., Ioannidis, J.P., Mokrysz, C., Nosek, B.A., Flint, J., Robinson, E.S. & Munafò, M.R. 2013. Power failure: why small sample size undermines the reliability of neuroscience. *Nature Reviews Neuroscience* 14(5). 365.

Buzy, W.M., Medoff, D.R. & Schweitzer, J.B. 2009. Intra-individual variability among children with adhd on a working memory task: an ex-gaussian approach. *Child Neuropsychology* 15(5). 441–459.

Cabeza, R., Anderson, N.D., Houle, S., Mangels, J.A. & Nyberg, L. 2000. Age-related differences in neural activity during item and temporal-order memory retrieval: a positron emission tomography study. *Journal of Cognitive Neuroscience* 12(1). 197–206.

Cabeza, R. & Dennis, N.A. 2013. Frontal lobes and aging: deterioration and compensation. In *Principles of frontal lobe function*, pp. 628–652. Oxford University Press.

Calabria, M., Hernández, M., Martin, C.D. & Costa, A. 2011. When the tail counts: the advantage of bilingualism through the ex-gaussian distribution analysis. *Frontiers in psychology* 2. 250.

Chee, M.W., Hon, N., Lee, H.L. & Soon, C.S. 2001. Relative language proficiency modulates bold signal change when bilinguals perform semantic judgments. *Neuroimage* 13(6). 1155–1163.

Chen, S.H., Zhou, Q., Uchikoshi, Y. & Bunge, S.A. 2014. Variations on the bilingual advantage? links of chinese and english proficiency to chinese american children's self-regulation. *Frontiers in psychology* 5. 1069.

Chertkow, H., Whitehead, V., Phillips, N., Wolfson, C., Atherton, J. & Bergman, H. 2010. Multilingualism (but not always bilingualism) delays the onset of alzheimer disease: evidence from a bilingual community. *Alzheimer Disease & Associated Disorders* 24(2). 118–125.

Clayson, P.E. & Larson, M.J. 2011. Conflict adaptation and sequential trial effects: Support for the conflict monitoring theory. *Neuropsychologia* 49(7). 1953–1961.

Cohen, J. 1962. The statistical power of abnormal-social psychological research: a review. *The Journal of Abnormal and Social Psychology* 65(3). 145.

Colomé, À. 2001. Lexical activation in bilinguals' speech production: Language-specific or language-independent? *Journal of memory and language* 45(4). 721–736.

Costa, A. & Sebastián-Gallés, N. 2014. How does the bilingual experience sculpt the brain? *Nature Reviews Neuroscience* 15(5). 336.

Cousineau, D., Goodman, V.W. & Shiffrin, R.M. 2002. Extending statistics of extremes to distributions varying in position and scale and the implications for race models. *Journal of Mathematical Psychology* 46(4). 431–454.

Craik, F.I., Bialystok, E. & Freedman, M. 2010. Delaying the onset of alzheimer disease bilingualism as a form of cognitive reserve. *Neurology* 75(19). 1726–1729.

Davidson, M.C., Amso, D., Anderson, L.C. & Diamond, A. 2006. Development of cognitive control and executive functions from 4 to 13 years: Evidence from manipulations of memory, inhibition, and task switching. *Neuropsychologia* 44(11). 2037–2078.

De Jong, R., Liang, C.-C. & Lauber, E. 1994. Conditional and unconditional automaticity: a dual-process model of effects of spatial stimulus-response correspondence. *Journal of Experimental Psychology: Human Perception and Performance* 20(4). 731.

Delignette-Muller, M.L., Dutang, C., et al. 2015. fitdistrplus: An r package for fitting distributions. *Journal of Statistical Software* 64(4). 1–34.

Diamond, A. 2013. Executive functions. *Annual review of psychology* 64. 135.

Dijkstra, T., Grainger, J. & Van Heuven, W.J. 1999. Recognition of cognates and interlingual homographs: The neglected role of phonology. *Journal of Memory and language* 41(4). 496–518.

Dijkstra, T., Van Heuven, W.J. & Grainger, J. 1998. Simulating cross-language competition with the bilingual interactive activation model. *Psychologica Belgica*.

Dove, A., Pollmann, S., Schubert, T., Wiggins, C.J., and von Cramon, D.Y. 2000. Prefrontal cortex activation in task switching: an event-related fmri study. *Cognitive brain research* 9(1). 103–109.

Duñabeitia, J.A. & Carreiras, M. 2015. The bilingual advantage: Acta est fabula. *Cortex* 73. 371–372.

Duñabeitia, J.A., Hernández, J.A., Antón, E., Macizo, P., Estévez, A., Fuentes, L.J. & Carreiras, M. 2014. The inhibitory advantage in bilingual children revisited. *Experimental psychology*.

Duthoo, W., Abrahamse, E.L., Braem, S., Boehler, C.N. & Notebaert, W. 2014. The congruency sequence effect 3.0: a critical test of conflict adaptation. *PloS one* 9(10).

Elston-Güttler, K.E., Paulmann, S. & Kotz, S.A. 2005. Who's in control? proficiency and l1 influence on l2 processing. *Journal of cognitive neuroscience* 17(10). 1593–1610.

Engel de Abreu, P.M., Cruz-Santos, A., Tourinho, C.J., Martin, R. & Bialystok, E. 2012. Bilingualism enriches the poor: Enhanced cognitive control in low-income minority children. *Psychological science* 23(11). 1364–1371.

Fabiani, M. 2012. It was the best of times, it was the worst of times: A psychophysiologist's view of cognitive aging. *Psychophysiology* 49(3). 283–304.

Fishman, J.A. 1980. Bilingualism and biculturism as individual and as societal phenomena. *Journal of Multilingual & Multicultural Development* 1(1). 3–15.

Fisk, J.E. & Warr, P. 1996. Age and working memory: the role of perceptual speed, the central executive, and the phonological loop. *Psychology and Aging* 11(2). 316.

for National Statistics, O. 2010. *Standard cccupational classification*. UK Statistics Authority.

Garavan, H., Ross, T. & Stein, E. 1999. Right hemispheric dominance of inhibitory control: an event-related functional mri study. *Proceedings of the National Academy of Sciences* 96(14). 8301–8306.

García-Pentón, L., Fernández, A.P., Iturria-Medina, Y., Gillon-Dowens, M. & Carreiras, M. 2014. Anatomical connectivity changes in the bilingual brain. *Neuroimage* 84. 495–504.

Gazzaley, A., Cooney, J.W., Rissman, J. & D'esposito, M. 2005. Top-down suppression deficit underlies working memory impairment in normal aging. *Nature neuroscience* 8(10). 1298.

Gold, B.T., Johnson, N.F. & Powell, D.K. 2013. Lifelong bilingualism contributes to cognitive reserve against white matter integrity declines in aging. *Neuropsychologia* 51(13). 2841–2846.
Gollan, T.H. & Acenas, L.-A.R. 2004. What is a tot? cognate and translation effects on tip-of-the-tongue states in spanish-english and tagalog-english bilinguals. *Journal of Experimental Psychology: Learning, Memory, and Cognition* 30(1). 246.
Gollan, T.H., Fennema-Notestine, C., Montoya, R.I. & Jernigan, T.L. 2007. The bilingual effect on boston naming test performance. *Journal of the International Neuropsychological Society* 13(2). 197–208.
Gollan, T.H., Montoya, R.I., Fennema-Notestine, C. & Morris, S.K. 2005. Bilingualism affects picture naming but not picture classification. *Memory & cognition* 33(7). 1220–1234.
Gollan, T.H., Montoya, R.I. & Werner, G.A. 2002. Semantic and letter fluency in spanish-english bilinguals. *Neuropsychology* 16(4). 562.
Gould, R., Brown, R., Owen, A., Howard, R., et al. 2003. fmri bold response to increasing task difficulty during successful paired associates learning. *Neuroimage* 20(2). 1006–1019.
Grant, A., Dennis, N.A. & Li, P. 2014. Cognitive control, cognitive reserve, and memory in the aging bilingual brain. *Frontiers in psychology* 5. 1401.
Green, D.W. 1998. Mental control of the bilingual lexico-semantic system. *Bilingualism: Language and cognition* 1(2). 67–81.
Green, D.W. & Abutalebi, J. 2013. Language control in bilinguals: The adaptive control hypothesis. *Journal of Cognitive Psychology* 25(5). 515–530.
Gu, S.-L.H., Gau, S.S.-F., Tzang, S.-W. & Hsu, W.-Y. 2013. The ex-gaussian distribution of reaction times in adolescents with attention-deficit/hyperactivity disorder. *Research in developmental disabilities* 34(11). 3709–3719.
Guo, T., Liu, H., Misra, M. & Kroll, J.F. 2011. Local and global inhibition in bilingual word production: fmri evidence from chinese–english bilinguals. *NeuroImage* 56(4). 2300–2309.
Habeck, C., Hilton, H.J., Zarahn, E., Flynn, J., Moeller, J. & Stern, Y. 2003. Relation of cognitive reserve and task performance to expression of regional covariance networks in an event-related fmri study of nonverbal memory. *Neuroimage* 20(3). 1723–1733.
Hackman, D.A. & Farah, M.J. 2009. Socioeconomic status and the developing brain. *Trends in cognitive sciences* 13(2). 65–73.
Hale, S., Myerson, J., Rhee, S.H., Weiss, C.S. & Abrams, R.A. 1996. Selective interference with the maintenance of location information in working memory. *Neuropsychology* 10(2). 228.
Heathcote, A., Popiel, S.J. & Mewhort, D. 1991. Analysis of response time distributions: An example using the stroop task. *Psychological Bulletin* 109(2). 340.
Hedge, A. & Marsh, N. 1975. The effect of irrelevant spatial correspondences on two-choice response-time. *Acta psychologica* 39(6). 427–439.
Hervais-Adelman, A.G., Moser-Mercer, B. & Golestani, N. 2011. Executive control of language in the bilingual brain: integrating the evidence from neuroimaging to neuropsychology. *Frontiers in psychology* 2. 234.

Hilchey, M., Saint-Aubin, J. & Klein, R. 2015. Does bilingual exercise enhance cognitive fitness in traditional non-linguistic executive processing tasks. *The Cambridge handbook of bilingual processing*, pp. 586–613.
Hockley, W.E. 1984. Analysis of response time distributions in the study of cognitive processes. *Journal of Experimental Psychology: Learning, Memory, and Cognition* 10(4). 598.
Hoenig, J.M. & Heisey, D.M. 2001. The abuse of power: the pervasive fallacy of power calculations for data analysis. *The American Statistician* 55(1). 19–24.
Hommel, B. 1993. The relationship between stimulus processing and response selection in the simon task: Evidence for a temporal overlap. *Psychological research* 55(4). 280–290.
Inouye, S.K., Albert, M.S., Mohs, R., Sun, K. & Berkman, L.F. 1993. Cognitive performance in a high-functioning community-dwelling elderly population. *Journal of Gerontology* 48(4):M146–M151.
Izura, C. & Ellis, A.W. 2004. Age of acquisition effects in translation judgement tasks. *Journal of Memory and Language* 50(2). 165–181.
Jack, C.R., Petersen, R., Xu, Y., Obrien, P., Smith, G., Ivnik, R., Boeve, B., Tangalos, E. & Kokmen, E. 2000. Rates of hippocampal atrophy correlate with change in clinical status in aging and ad. *Neurology* 55(4). 484–490.
Jessner, U. 2014. On multilingual awareness or why the multilingual learner is a specific language learner. In *Essential topics in applied linguistics and multilingualism*, pp. 175–184. Springer.
Johnson, P.C., Barry, S.J., Ferguson, H.M. & Müller, P. 2015. Power analysis for generalized linear mixed models in ecology and evolution. *Methods in ecology and evolution* 6(2). 133–142.
Kaplan, G.A., Turrell, G., Lynch, J.W., Everson, S.A., Helkala, E.-L. & Salonen, J.T. 2001. Childhood socioeconomic position and cognitive function in adulthood. *International journal of epidemiology* 30(2). 256–263.
Kaushanskaya, M. & Marian, V. 2007. Bilingual language processing and interference in bilinguals: Evidence from eye tracking and picture naming. *Language Learning* 57(1). 119–163.
Kavé, G., Eyal, N., Shorek, A. & Cohen-Mansfield, J. 2008. Multilingualism and cognitive state in the oldest old. *Psychology and aging* 23(1). 70.
Kenward, M.G. & Roger, J.H. 1997. Small sample inference for fixed effects from restricted maximum likelihood. *Biometrics*, pp. 983–997.
Kerns, J.G., Cohen, J.D., MacDonald, A.W., Cho, R.Y., Stenger, V.A. & Carter, C.S. 2004. Anterior cingulate conflict monitoring and adjustments in control. *Science* 303(5660). 1023–1026.
Kirk, N.W., Fiala, L., Scott-Brown, K.C. & Kempe, V. 2014. No evidence for reduced simon cost in elderly bilinguals and bidialectals. *Journal of Cognitive Psychology* 26(6). 640–648.
Knight, J. & Nigam, Y. 2017. Anatomy and physiology of ageing 5: the nervous system. *Nursing Times* 113(6). 55–58.
Kornblum, S. & Lee, J.-W. 1995. Stimulus-response compatibility with relevant and irrelevant stimulus dimensions that do and do not overlap with the response. *Journal of Experimental Psychology: Human Perception and Performance* 21(4). 855.

Kroll, J.F. & Bialystok, E. 2013. Understanding the consequences of bilingualism for language processing and cognition. *Journal of Cognitive Psychology* 25(5). 497–514.

Kroll, J.F., Bobb, S.C. & Hoshino, N. 2014. Two languages in mind: Bilingualism as a tool to investigate language, cognition, and the brain. *Current Directions in Psychological Science* 23(3). 159–163.

Kroll, J.F., Van Hell, J.G., Tokowicz, N. & Green, D.W. 2010. The revised hierarchical model: A critical review and assessment. *Bilingualism: Language and Cognition* 13(3). 373–381.

Kuhl, P.K. 2004. Early language acquisition: cracking the speech code. *Nature reviews neuroscience* 5(11). 831.

Kuznetsova, A., Brockhoff, P.B. & Christensen, R.H. B. 2017. lmertest package: tests in linear mixed effects models. *Journal of Statistical Software* 82(13).

Kuznetsova, A., Brockhoff, P.B., Christensen, R.H. B., et al. 2015. Package lmertest. *R package version* 2(0).

Lacouture, Y. & Cousineau, D. 2008. How to use matlab to fit the ex-gaussian and other probability functions to a distribution of response times. *Tutorials in Quantitative Methods for Psychology* 4(1). 35–45.

Larson, M.J., Clayson, P.E., Keith, C.M., Hunt, I.J., Hedges, D.W., Nielsen, B.L. & Call, V.R. 2016. Cognitive control adjustments in healthy older and younger adults: Conflict adaptation, the error-related negativity (ern), and evidence of generalized decline with age. *Biological Psychology* 115. 50–63.

Larson, M.J., Kaufman, D.A. & Perlstein, W.M. 2009. Neural time course of conflict adaptation effects on the stroop task. *Neuropsychologia* 47(3). 663–670.

Lawrence, B., Myerson, J. & Hale, S. 1998. Differential decline of verbal and visuospatial processing speed across the adult life span. *Aging, Neuropsychology, and Cognition* 5(2). 129–146.

Le Carret, N., Lafont, S., Letenneur, L., Dartigues, J.-F., Mayo, W. & Fabrigoule, C. 2003. The effect of education on cognitive performances and its implication for the constitution of the cognitive reserve. *Developmental neuropsychology* 23(3). 317–337.

Li, P., Legault, J. & Litcofsky, K.A. 2014. Neuroplasticity as a function of second language learning: anatomical changes in the human brain. *Cortex* 58. 301–324.

López-López, J.A., Marín-Martínez, F., Sánchez-Meca, J., Van den Noortgate, W. & Viechtbauer, W. 2014. Estimation of the predictive power of the model in mixed-effects meta-regression: A simulation study. *British Journal of Mathematical and Statistical Psychology* 67(1). 30–48.

Lucci, G., Berchicci, M., Spinelli, D., Taddei, F. & Di Russo, F. 2013. The effects of aging on conflict detection. *PloS one* 8(2).

Luce, R.D. et al. 1986. *Response times: Their role in inferring elementary mental organization*. Number 8 in Oxford Psychology Series. Oxford University Press.

Luk, G. & Bialystok, E. 2013. Bilingualism is not a categorical variable: Interaction between language proficiency and usage. *Journal of Cognitive Psychology* 25(5). 605–621.

Luk, G., Bialystok, E., Craik, F.I. & Grady, C.L. (2011a). Lifelong bilingualism maintains white matter integrity in older adults. *Journal of Neuroscience* 31(46). 16808–16813.

Luk, G., De Sa, E. & Bialystok, E. (2011b). Is there a relation between onset age of bilingualism and enhancement of cognitive control? *Bilingualism: Language and Cognition* 14(4). 588–595.

Madden, D.J., Whiting, W.L., Huettel, S.A., White, L.E., MacFall, J.R. & Provenzale, J.M. 2004. Diffusion tensor imaging of adult age differences in cerebral white matter: relation to response time. *Neuroimage* 21(3). 1174–1181.

Mapelli, D., Rusconi, E. & Umiltà, C. 2003. The snarc effect: an instance of the simon effect? *Cognition* 88(3):B1–B10.

Marioni, R.E., van den Hout, A., Valenzuela, M.J., Brayne, C., Matthews, F.E., et al. 2012. Active cognitive lifestyle associates with cognitive recovery and a reduced risk of cognitive decline. *Journal of Alzheimer's Disease* 28(1). 223–230.

Marmolejo-Ramos, F., Cousineau, D., Benites, L. & Maehara, R. 2015. On the efficacy of procedures to normalize ex-gaussian distributions. *Frontiers in psychology* 5. 1548.

Matuschek, H., Kliegl, R., Vasishth, S., Baayen, H. & Bates, D. 2017. Balancing type i error and power in linear mixed models. *Journal of Memory and Language* 94. 305–315.

Matzke, D. & Wagenmakers, E.-J. 2009. Psychological interpretation of the ex-gaussian and shifted wald parameters: A diffusion model analysis. *Psychonomic bulletin & review* 16(5). 798–817.

McGill, W.J. & Gibbon, J. 1965. The general-gamma distribution and reaction times. *Journal of Mathematical Psychology* 2(1). 1–18.

Meuter, R.F. & Allport, A. 1999. Bilingual language switching in naming: Asymmetrical costs of language selection. *Journal of memory and language* 40(1). 25–40.

Mink, J.W. & Thach, W.T. 1993. Basal ganglia intrinsic circuits and their role in behavior. *Current opinion in neurobiology* 3(6). 950–957.

Mistridis, P., Mata, J., Neuner-Jehle, S., Annoni, J.-M., Biedermann, A., Bopp-Kistler, I., Brand, D., Brioschi Guevara, A., Decrey-Wick, H., Démonet, J.-F., et al. 2017. Use it or lose it! cognitive activity as a protec-tive factor for cognitive decline associated with alzheimer's disease. *Swiss medical weekly* 147:w14407.

Miyake, A. & Friedman, N.P. 2012. The nature and organization of individual differences in executive functions: Four general conclusions. *Current directions in psychological science* 21(1). 8–14.

Miyake, A., Friedman, N.P., Emerson, M.J., Witzki, A.H., Howerter, A. & Wager, T.D. 2000. The unity and diversity of executive functions and their contributions to complex frontal lobe tasks: A latent variable analysis. *Cognitive psychology* 41(1). 49–100.

Monchi, O., Petrides, M., Petre, V., Worsley, K. & Dagher, A. 2001. Wisconsin card sorting revisited: distinct neural circuits participating in different stages of the task identified by event-related functional magnetic resonance imaging. *Journal of Neuroscience* 21(19). 7733–7741.

Myerson, J., Hale, S., Rhee, S.H. & Jenkins, L. 1999. Selective interference with verbal and spatial working memory in young and older adults. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences* 54(3):P161–P164.

Myung, I.J. 2003. Tutorial on maximum likelihood estimation. *Journal of mathematical Psychology* 47(1). 90–100.

Noble, K.G., Norman, M.F. & Farah, M.J. 2005. Neurocognitive correlates of socioeconomic status in kindergarten children. *Developmental science* 8(1). 74–87.

Nucci, M., Mapelli, D. & Mondini, S. 2012. Cognitive reserve index questionnaire (criq): a new instrument for measuring cognitive reserve. *Aging clinical and experimental research* 24(3). 218–226.

Nyberg, L., Lövdén, M., Riklund, K., Lindenberger, U. & Bäckman, L. 2012. Memory aging and brain maintenance. *Trends in cognitive sciences* 16(5). 292–305.

Opdebeeck, C., Martyr, A. & Clare, L. 2016. Cognitive reserve and cognitive function in healthy older people: a meta-analysis. *Aging, Neuropsychology, and Cognition* 23(1). 40–60.

Paap, K.R. & Greenberg, Z.I. 2013. There is no coherent evidence for a bilingual advantage in executive processing. *Cognitive psychology* 66(2). 232–258.

Paap, K.R., Johnson, H.A. & Sawi, O. 2015. Bilingual advantages in executive functioning either do not exist or are restricted to very specific and undetermined circumstances. *Cortex* 69. 265–278.

Peirce, J.W. 2007. Psychopypsychophysics software in python. *Journal of neuroscience methods* 162(1-2). 8–13.

Perani, D., Abutalebi, J., Paulesu, E., Brambati, S., Scifo, P., Cappa, S.F. & Fazio, F. 2003. The role of age of acquisition and language usage in early, high-proficient bilinguals: An fmri study during verbal fluency. *Human brain mapping* 19(3). 170–182.

Perani, D., Dehaene, S., Grassi, F., Cohen, L., Cappa, S.F., Dupoux, E., Fazio, F. & Mehler, J. 1996. Brain processing of native and foreign languages. *NeuroReport-International Journal for Rapid Communications of Research in Neuroscience* 7(15). 2439–2444.

Perani, D., Paulesu, E., Galles, N.S., Dupoux, E., Dehaene, S., Bettinardi, V., Cappa, S.F., Fazio, F. & Mehler, J. 1998. The bilingual brain. proficiency and age of acquisition of the second language. *Brain: a journal of neurology* 121(10). 1841–1852.

Perea, M., Dunabeitia, J.A. & Carreiras, M. 2008. Masked associative/semantic priming effects across languages with highly proficient bilinguals. *Journal of Memory and Language* 58(4). 916–930.

Pérès, K., Helmer, C., Amieva, H., Orgogozo, J.-M., Rouch, I., Dartigues, J.-F. & Barberger-Gateau, P. 2008. Natural history of decline in instrumental activities of daily living performance over the 10 years preceding the clinical diagnosis of dementia: a prospective population-based study. *Journal of the American Geriatrics Society* 56(1). 37–44.

Perianez, J., Rios-Lago, M., Rodriguez-Sanchez, J., Adrover-Roig, D., Sanchez-Cubillo, I., Crespo-Facorro, B., Quemada, J. & Barcelo, F. 2007. Trail making test in traumatic brain injury, schizophrenia, and normal ageing: Sample comparisons and normative data. *Archives of Clinical Neuropsychology* 22(4). 433–447.

Perquin, M., Vaillant, M., Schuller, A.-M., Pastore, J., Dartigues, J.-F., Lair, M.-L., Diederich, N., Group, M., et al. 2013. Lifelong exposure to multilingualism: new evidence to support cognitive reserve hypothesis. *PloS one* 8(4):e62030.

Peyer, E., Kaiser, I. & Berthele, R. 2010. The multilingual reader: Advantages in understanding and decoding german sentence structure when reading german as an l3. *International Journal of Multilingualism* 7(3). 225–239.

Pfenninger, S.E. 2014. Quadrilingual advantages: Do-support in bilingual vs. multilingual learners. *International Journal of Multilingualism* 11(2). 143–163.

Pinheiro, J. & Bates, D. 2006. *Mixed-effects models in S and S-PLUS*.Springer Science & Business Media.

Pliatsikas, C., Moschopoulou, E. & Saddy, J.D. 2015. The effects of bilingualism on the white matter structure of the brain. *Proceedings of the National Academy of Sciences* 112(5). 1334–1337.

Poarch, G.J. and van Hell, J.G. 2012. Executive functions and inhibitory control in multilingual children: Evidence from second-language learners, bilinguals, and trilinguals. *Journal of experimental child psychology* 113(4). 535–551.

Portocarrero, J.S., Burright, R.G. & Donovick, P.J. 2007. Vocabulary and verbal fluency of bilingual and monolingual college students. *Archives of Clinical Neuropsychology* 22(3). 415–422.

Prakash, R.S., Erickson, K.I., Colcombe, S.J., Kim, J.S., Voss, M.W. & Kramer, A.F. 2009. Age-related differences in the involvement of the prefrontal cortex in attentional control. *Brain and cognition* 71(3). 328–335.

Price, R.B., Brown, V. & Siegle, G.J. 2019. Computational modeling applied to the dot-probe task yields improved reliability and mechanistic insights. *Biological psychiatry* 85(7). 606–612.

Puccioni, O. & Vallesi, A. 2012. Conflict resolution and adaptation in normal aging: the role of verbal intelligence and cognitive reserve. *Psychology and Aging* 27(4). 1018.

R Core Team (2013). R: A language and environment for statistical computing. *The R project*.

Ransdell, S.E. & Fischler, I. 1987. Memory in a monolingual mode: When are bilinguals at a disadvantage? *Journal of Memory and Language* 26(4). 392–405.

Ratcliff, R. & McKoon, G. 2008. The diffusion decision model: theory and data for two-choice decision tasks. *Neural computation* 20(4). 873–922.

Ratcliff, R., Thapar, A., Gomez, P. & McKoon, G. 2004. A diffusion model analysis of the effects of aging in the lexical-decision task. *Psychology and aging* 19(2). 278.

Regier, T. & Kay, P. 2009. Language, thought, and color: Whorf was half right. *Trends in cognitive sciences* 13(10). 439–446.

Roberts, P.M., Garcia, L.J., Desrochers, A. & Hernandez, D. 2002. English performance of proficient bilingual adults on the boston naming test. *Aphasiology* 16(4-6). 635–645.

Rodríguez, J.L. S., Torrellas, C., Martín, J. & Fernandez, M.J. 2011. Cognitive reserve and lifestyle in spanish individuals with sporadic alzheimers disease. *American Journal of Alzheimer's Disease & Other Dementias®*, 26(7). 542–554.

Rogers, C.L., Lister, J.J., Febo, D.M., Besing, J.M. & Abrams, H.B. 2006. Effects of bilingualism, noise, and reverberation on speech perception by listeners with normal hearing. *Applied Psycholinguistics* 27(3). 465–485.

Roldán-Tapia, L., García, J., Cánovas, R. & León, I. 2012. Cognitive reserve, age, and their relation to attentional and executive functions. *Applied Neuropsychology: Adult* 19(1). 2–8.

Rosselli, M., Ardila, A., Araujo, K., Weekes, V.A., Caracciolo, V., Padilla, M. & Ostrosky-Solí, F. 2000. Verbal fluency and repetition skills in healthy older spanish-english bilinguals. *Applied neuropsychology* 7(1). 17–24.

Salthouse, T.A. 1996. The processing-speed theory of adult age differences in cognition. *Psychological review* 103(3). 403.

Salthouse, T.A. & Davis, H.P. 2006. Organization of cognitive abilities and neuropsychological variables across the lifespan. *Developmental Review* 26(1). 31–54.

Salthouse, T.A., Pink, J.E. & Tucker-Drob, E.M. 2008. Contextual analysis of fluid intelligence. *Intelligence* 36(5). 464–486.

Scarmeas, N., Levy, G., Tang, M.-X., Manly, J. & Stern, Y. 2001. Influence of leisure activity on the incidence of alzheimers disease. *Neurology* 57(12). 2236–2242.

Schaalje, G.B., McBride, J.B. & Fellingham, G.W. 2002. Adequacy of approximations to distributions of test statistics in complex mixed linear models. *Journal of Agricultural, Biological, and Environmental Statistics* 7(4). 512.

Schaie, K.W. & Zanjani, F.A. 2006. Intellectual development across adulthood. *Handbook of adult development and learning*, pp. 99–122.

Schmidt, R., Fazekas, F., Kapeller, P., Schmidt, H. & Hartung, H.-P. 1999. Mri white matter hyperintensities: three-year follow-up of the austrian stroke prevention study. *Neurology* 53(1). 132–132.

Schneeweis, N., Skirbekk, V. & Winter-Ebmer, R. 2014. Does education improve cognitive performance four decades after school completion? *Demography* 51(2). 619–643.

Schroeder, S.R. & Marian, V. 2012. A bilingual advantage for episodic memory in older adults. *Journal of Cognitive Psychology* 24(5). 591–601.

Schweizer, T.A., Ware, J., Fischer, C.E., Craik, F.I. & Bialystok, E. 2012. Bilingualism as a contributor to cognitive reserve: Evidence from brain atrophy in alzheimer's disease. *Cortex* 48(8). 991–996.

Seidenberg, M.S. & Zevin, J.D. 2006. Connectionist models in developmental cognitive neuroscience: Critical periods and the paradox of success. *Attention & Performance XXI: Processes of change in brain and cognitive development*, pp. 585–612.

Silva-Corvalán, C. 1997. *Spanish in four continents: Studies in language contact and bilingualism*. Georgetown University Press.

Simon, J.R. 1990. The effects of an irrelevant directional cue on human information processing. In *Advances in psychology*, volume 65, pp. 31–86. Elsevier.

Simon, J.R. & Rudell, A.P. 1967. Auditory sr compatibility: the effect of an irrelevant cue on information processing. *Journal of applied psychology* 51(3). 300.

Siok, W.T., Kay, P., Wang, W.S., Chan, A.H., Chen, L., Luke, K.-K. & Tan, L.H. 2009. Language regions of brain are operative in color perception. *Proceedings of the National Academy of Sciences* 106(20). 8140–8145.

Soveri, A., Rodriguez-Fornells, A. & Laine, M. 2011. Is there a relationship between language switching and executive functions in bilingualism? introducing a within group analysis approach. *Frontiers in Psychology* 2. 183.

Stasinopoulos, D.M., Rigby, R.A., et al. 2007. Generalized additive models for location scale and shape (gamlss) in r. *Journal of Statistical Software* 23(7). 1–46.

Steinhauser, M. & Hübner, R. 2009. Distinguishing response conflict and task conflict in the stroop task: evidence from ex-gaussian distribution analysis. *Journal of Experimental Psychology: Human Perception and Performance* 35(5). 1398.

Stern, Y. 2002. What is cognitive reserve? theory and research application of the reserve concept. *Journal of the International Neuropsychological Society* 8(03). 448–460.

Stern, Y. 2009. Cognitive reserve. *Neuropsychologia* 47(10). 2015–2028.

Stern, Y. 2012. Cognitive reserve in ageing and alzheimer's disease. *The Lancet Neurology* 11(11). 1006–1012.

Stern, Y., Barnes, C.A., Grady, C., Jones, R.N. & Raz, N. 2019. Brain reserve, cognitive reserve, compensation, and maintenance: operationalization, validity, and mechanisms of cognitive resilience. *Neurobiology of aging* 83. 124–129.

Stevens, M. & Brysbaert, M. 2016. When do we have enough power in language research? evidence from priming studies. *Unpublished ms, Ghent University*.

Stürmer, B., Leuthold, H., Soetens, E., Schröter, H. & Sommer, W. 2002. Control over location-based response activation in the simon task: behavioral and electrophysiological evidence. *Journal of Experimental Psychology: Human Perception and Performance* 28(6). 1345.

Summerfield, C. & Egner, T. 2009. Expectation (and attention) in visual cognition. *Trends in cognitive sciences* 13(9). 403–409.

Sunaert, S., Van Hecke, P., Marchal, G. & Orban, G.A. 2000. Attention to speed of motion, speed discrimination, and task difficulty: an fmri study. *Neuroimage* 11(6). 612–623.

Suo, C., León, I., Brodaty, H., Trollor, J., Wen, W., Sachdev, P. & Valenzuela, M.J. 2012. Supervisory experience at work is linked to low rate of hippocampal atrophy in late life. *Neuroimage* 63(3). 1542–1551.

Swainson, R., Cunnington, R., Jackson, et al. 2003. Cognitive control mechanisms revealed by erp and fmri: evidence from repeated task-switching. *Journal of Cognitive Neuroscience* 15(6). 785–799.

Swick, D. & Jovanovic, J. 2002. Anterior cingulate cortex and the stroop task: neuropsychological evidence for topographic specificity. *Neuropsychologia* 40(8). 1240–1253.

Thierry, G., Athanasopoulos, P., Wiggett, A., Dering, B. & Kuipers, J.-R. 2009. Unconscious effects of language-specific terminology on preattentive color perception. *Proceedings of the National Academy of Sciences* 106(11). 4567–4570.

Ulrich, R. & Miller, J. 1993. Information processing models generating lognormally distributed reaction times. *Journal of Mathematical Psychology* 37. 513–513.

Umiltà, C. & Nicoletti, R. 1985. Attention and coding effects in sr compatibility due to irrelevant spatial cues. *Attention and performance XI*, pp. 457–471.

Valenzuela, M., Brodaty, H., Wen, W., Chen, X. & Sachdev, P. 2009. Lifespan mental activity predicts diminished rate of hippocampal atrophy. *Alzheimer's & Dementia: The Journal of the Alzheimer's Association* 5(5):e9.

van Heuven, W.J. & Dijkstra, T. 2010. Language comprehension in the bilingual brain: fmri and erp support for psycholinguistic models. *Brain research reviews* 64(1). 104–122.

Van Zandt, T. 2000. How to fit a response time distribution. *Psychonomic bulletin & review* 7(3). 424–465.
Von Bastian, C.C., Souza, A.S. & Gade, M. 2016. No evidence for bilingual cognitive advantages: A test of four hypotheses. *Journal of Experimental Psychology: General* 145(2). 246.
Voss, A., Nagler, M. & Lerche, V. 2013. Diffusion models in experimental psychology. *Experimental psychology*.
Voss, A., Voss, J. & Lerche, V. 2015. Assessing cognitive processes with diffusion model analyses: a tutorial based on fast-dm-30. *Frontiers in psychology* 6. 336.
Wagenmakers, E.-J. 2009. Methodological and empirical developments for the ratcliff diffusion model of response times and accuracy. *European Journal of Cognitive Psychology* 21(5). 641–671.
Wang, M., Gamo, N.J., Yang, Y., Jin, L.E., Wang, X.-J., Laubach, M., Mazer, J.A., Lee, D. & Arnsten, A.F. 2011. Neuronal basis of age-related working memory decline. *Nature* 476(7359). 210.
Wartenburger, I., Heekeren, H.R., Abutalebi, J., Cappa, S.F., Villringer, A. & Perani, D. 2003. Early setting of grammatical processing in the bilingual brain. *Neuron* 37(1). 159–170.
Weber-Fox, C.M. & Neville, H.J. 1996. Maturational constraints on functional specializations for language processing: Erp and behavioral evidence in bilingual speakers. *Journal of cognitive neuroscience* 8(3). 231–256.
West, R. & Moore, K. 2005. Adjustments of cognitive control in younger and older adults. *Cortex* 41(4). 570–581.
West, R.L. 1996. An application of prefrontal cortex function theory to cognitive aging. *Psychological bulletin* 120(2). 272.
Will, B., Dalrymple-Alford, J., Wolff, M. & Cassel, J.-C. 2008. The concept of brain plasticitypaillard's systemic analysis and emphasis on structure and function (followed by the translation of a seminal paper by paillard on plasticity). *Behavioural brain research* 192(1). 2–7.
Winter, B. 2013. Linear models and linear mixed effects models in r with linguistic applications. *arXiv preprint arXiv. 1308.5499*.
Zahodne, L.B., Stern, Y. & Manly, J.J. 2015. Differing effects of education on cognitive decline in diverse elders with low versus high educational attainment. *Neuropsychology* 29(4). 649.
Zorzi, M. & Umiltá, C. 1995. A computational model of the simon effect. *Psychological Research* 58(3). 193–205.

Corresponding author:
Panagiotis Boutris
Centre for Children and Families
Florida International University (MMC)
11200 SW 8th Street
AHC 4
Miami, Florida 33199, USA
pboutris@fiu.edu